SONIC TEST FOR THE EVALUATION OF STRIPPING RESISTANCE IN COMPACTED BITUMINOUS MIXTURES

FEBRUARY, 1956
No. 7

by
Orlando B. Andersland

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

SONIC TEST FOR EVALUATION OF

STRIPPING RESISTANCE IN COMPACTED BITUMINOUS MIXTURES

TO: K. B. Woods, Director
Joint Highway Research Project

February 1, 1956

File: 2-5-1-1
C-36-8C

FROM: Harold L. Michael, Assistant Director

The attached report entitled "Sonic Test for Evaluation of Stripping Resistance in Compacted Bituminous Mixtures" was prepared by Mr. O. B. Andersland, Graduate Assistant, and was used by him as a thesis for his degree of M.S.C.E. The work was conducted in the bituminous laboratory under the supervision of Professor Goetz and represents an extension of the work utilizing the sonic test in the evaluation of bituminous mixtures.

Although the study was somewhat limited in scope, particularly with respect to the types of bituminous mixtures to which it was applied, the data indicate that the sonic test method may be utilized to evaluate stripping resistance in bituminous mixtures. It is strongly indicated that a standard sonic test method could be prepared which would have several advantages over the present standard A.S.T.M. Immersion-Compression Test.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Assistant Director
Joint Highway Research Project

HLM:cjg

Attachment

cc: J. R. Cooper
J. T. Hallett
F. F. Havey
G. A. Hawkins
G. A. Leonards
B. B. Lewis
R. E. Mills
B. H. Petty
Lloyd Poindexter
C. E. Vogelgesang
J. L. Waling

SONIC TEST FOR EVALUATION OF

STRIPPING RESISTANCE IN COMPACTED BITUMINOUS MIXTURES

by

Orlando Baldwin Andersland

Graduate Assistant

Joint Highway Research Project

File: 2-5-1-1

C-36-8C

Purdue University
Lafayette, Indiana

February 1, 1956

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Professor W. H. Goetz, Research Engineer, Joint Highway Research Project, for the generous time and effort he gave in the direction of this investigation.

Special thanks are due Mr. J. F. McLaughlin, Research Engineer, Joint Highway Research Project, for his valuable suggestions and Mr. L. E. Wood, Research Engineer, Joint Highway Research Project, for his original ideas for the roller compaction equipment and other suggestions.

The writer is grateful to the Joint Highway Research Project, Purdue University, for the use of their laboratory facilities, materials, special equipment, and part-time student help provided for use in this investigation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

Figure Page

ABSTRACT

Andersland, Orlando Baldwin. M.S.C.E. Purdue University, January 1956. Sonic Test for the Evaluation of Stripping Resistance in Compacted Bituminous Mixtures. Major Professor: W. H. Goetz.

This laboratory study attempts to determine the application of the Sonic Test for the evaluation of stripping resistance in compacted bituminous mixtures exposed to water. Tests are conducted on beam specimens molded from materials the same as those used in the construction of a high-type bituminous concrete pavement. Specimens are subjected to severe exposure of water under prescribed conditions of temperature and time. These conditions cause deterioration in the specimens similar to what could be expected in the field over a much greater period of time.

Other tests used to determine stripping resistance are described briefly. Two of the more accepted tests, the Immersion-Compression Test and the Visual Stripping Test, are used in this study for a comparison with results obtained by the Sonic Test. Three aggregates and one asphalt are used to show different degrees of stripping for the tests used. An asphalt bonding additive was used in one group of specimens for the Sonic Test. Another group of specimens included a different gradation to show what effect this had on the Sonic Test results.

The compaction method used in molding the beam specimens follows partly the procedure used in earlier work. An improvement is made on the method which includes rolling action to simulate rolling action received by a bituminous pavement in field construction. Several sketches and pictures illustrate the equipment used in molding the beam specimens.

Results of this study indicate that the Sonic Test can be used advantageously in the evaluation of stripping resistance of compacted bituminous mixtures. The hydrophilic properties of the rhyolite aggregate were shown by the Sonic Test as well as or better than they were shown by the other two tests used in the study. Test procedures used in the Sonic Test for preparing the specimens, weathering, and testing, make it suitable for use in research work or use in checking a group of construction materials.

SWELL TEST
FOR EVALUATION OF STRIPPING RESISTANCE
IN COMPACTED BITUMINOUS MIXTURES

INTRODUCTION

Compacted bitumen-aggregate mixtures used for road surfaces show various degrees of durability when exposed to the weathering action of water in either the liquid or vapor form. Under service conditions road surfaces may fail because of a loss in stability brought about by a decrease in adhesion between the bituminous material and the aggregate. In "Bituminous-Aggregate Water Resistance Studies" by Krchma and Loomis (1)[1], results showed that from the service viewpoint, lack of water resistance by bituminous surfacing involves primarily a loss of strength or stability due to water action. A good adhesive bond between the bituminous material and the aggregate is required for stability in the road surface (2).

Studies of bituminous pavements affected by loss in adhesive bond show that the action in most cases begins at the bottom of the pavement and slowly progresses upward, its rate of progress generally depending

---

[1] Numbers in parentheses refer to references listed in Bibliography.

on certain characteristics of the bitumen-aggregate mixture. This upward progress of the stripping action often stops somewhere below the pavement surface depending on the porosity of the upper portion of the pavement (3). Stripping is not frequent in the upper portion of the pavement for two reasons: first, because the wearing course is denser than the base or binder and is often protected from the action of surface moisture by a seal coat and, second, evaporation of any water which accumulates in the voids is more rapid in the upper than in the lower portion of the pavement (4). The extent of this type of damage is not readily apparent from superficial observation until after the pavement has failed over a large area.

An example of a surface failure on a bituminous mat composed of SC-3 material and local aggregates occurred in the spring of 1942 on an experimental road surfacing project conducted by the Colorado State Highway Department in co-operation with the Public Roads Administration (5). Rapid deterioration of the surface began with the first rains, the surface softened to a slight depth after each rain and became slimy under traffic. Upon drying the surface raveled, leaving the larger aggregate particles exposed. The modified Nicholson test procedure used on the Colorado aggregate did not show sufficient evidence to warrant a prediction of the type of failure that occurred on the test sections.

Failures in adhesion of bitumen-aggregate mixtures appear to be due to the displacement of the binder by water, although other factors, such as the abrasion by traffic must influence the process (6). "Asphalt has practically no affinity for water and if a water film exists between it and an aggregate surface, adhesion of the asphalt to

that asphalt is [illegible]. [illegible] aggregates on the other hand have an affinity for both asphalt and water. If the affinity of an aggregate for water is much greater than for asphalt then under certain conditions water may displace on asphalt with which it is coated" (7).

Adhesion between the bituminous material and the aggregate arises from their surface properties and will be affected by the following factors (6): 1. Surface tension of both the liquid and the solid surfaces; 2. Adsorption of the liquid on the surface of the solid; 3. Chemical action of the liquid on the solid; 4. Surface texture of the solid; 5. Porosity of the solid; 6. Viscosity of the liquid; and 7. Cleanness and freedom from moisture of the solid and liquid surfaces. In addition to surface properties, other factors including binder content, gradation of the aggregate, voids, and other compacted bituminous surfacing features have some bearing on water resistance where field service is concerned (1).

Various methods for evaluating the resistance to displacement by water of the bitumen in bitumen-aggregate mixtures have been included in many specifications in recent years. A suitable laboratory test method should permit the selection of the best combination of bitumen, available aggregate, and type of paving mixture to use for specific service requirements (18).

Present test methods for evaluating the adhesive characteristics of bitumen-aggregate mixtures employ a destructive test (Immersion-Compression) or a form of visual stripping test. The immersion-compression test is intended to measure the loss of cohesion resulting from the action of water on compacted bituminous mixtures containing penetration grade asphalts. A numerical index of reduced cohesion is

obtained by comparing the compressive strength of freshly molded and cured specimens with the compressive strength of duplicate specimens that have been immersed in water under prescribed conditions. The stripping tests measure the resistance of bituminous films on coated aggregates towards loosening and removal by action of water or moisture. The stripping resistance evaluation is made by visually estimating the percentage of the area of the aggregate remaining coated after immersion in water under specified conditions.

The work herein reported was performed in an attempt to determine the practical application of the Sonic Test to obtaining a measure of the durability of compacted bitumen-aggregate mixtures exposed to water under prescribed conditions. The A.S.T.M. "Standard Method of Test for Effect of Water on Cohesion of Compacted Bituminous Mixtures" and the provisional A.S.T.M. "Static Immersion Stripping Resistance Test" were performed on the same bitumen-aggregate mixtures or materials in order to obtain a comparison with the results from the Sonic Test.

REVIEW OF LITERATURE

The problem of loss in durability and stability of compacted bitumen-aggregate mixtures exposed to water began to attract major interest about 1940. The earliest studies, around 1922, were on the influence of absorbed colloids, and on preferential wetting problems from the chemical point of view (8). From these studies and later ones, about 40 different tests were developed including wash tests (8), swell tests (8), partition test (15), capillary tube method (13), use of radioactive isotopes in the determination of asphalt stripping from paving stone (30), and others. A brief discussion of some of these tests are included in the Historical section. The visual stripping-resistance test discussed in the next section was developed during the same period as those tests mentioned above and employed various procedures in preparing the mixtures and observation. Later the Immersion-Compression Test was developed to eliminate certain serious disadvantages common to all stripping tests. A section on the Immersion-Compression Test is included after the Visual Stripping-Resistance Test. To complete the review of literature is the section on the Sonic Test. It includes a short list of other uses and a description of its application to bituminous paving mixtures.

Historical

As the problem of stripping began to take shape and differences of opinion appeared on the cause of stripping, numerous tests were developed based on different ideas for the determination of loss in adhesion. Among the earlier tests was the Water-Oil Preferential Test developed by Efferts (9) in 1930 and adopted by Hveem of

California the same year. Texas and Arizona simultaneously began using a swell test (8).

Nicholson (13), using the capillary tube method, determined the adhesion tension of 13 different petroleum crudes for silica. These values ranged from 5[illegible].37 to 72.68 dynes/sq cm, as compared to 82.64 dynes/sq cm for water-silica interfaces. This explains the tendency of water to displace oils from crude-oil formations and also is associated with the stripping tendency of asphalts from mineral aggregates.

Riedel and Weber (10) in 1933 used a method for the determination of adhesiveness where 71 percent by volume of a specified grain-size aggregate is mixed with 29 percent by volume of the hot liquid bitumen. After cooling, a sample of the mixture is boiled for one minute in a test tube with water. If separation is effected by this treatment, the aggregate in question is not as well wetted by the bitumen as by water; therefore, there is small adhesion between the two. If the materials cannot be separated, then the adhesion is good. A later improvement to this method used Na_2CO_3 solutions of various concentrations for immersion of the stone-asphalt mixture. The higher the concentration of Na_2CO_3 which is required to strip the asphalt, the better the adhesivity.

Mack (14) in his study, "Physiocochemical Aspects of Asphalt Pavements: Energy Relations at Interface Between Asphalt and Mineral Aggregate and Their Measurements", devised a simple method to measure interfacial tension between solids and liquids which allows the powdered solid to settle freely from the liquid. With few exceptions the

volume to which the powder settles is proportional to the interfacial tension between the two phases. In the cases cited here, for hydrophilic silica, limestone, and blue clay, the settling volumes of the powders decrease with the interfacial tension of the liquid, and increase for the hydrophobic carbon black. Extended to asphalts, this relationship does not hold. For example, silica has an interfacial tension against the six asphalts investigated which are higher than those against water. Limestone and blue clay have negative interfacial tensions against the asphalts. The deviation from pure liquids is ascribed to a difference in absorption of certain asphaltic components and water on the surface of the solid.

Several tests for determining the relative resistance of asphalt to displacement by water from aggregate surfaces are described by Holmes (15) in the Proceedings of the American Society for Testing Materials., Volume 39. These include a partition test in which the rating is made by determining the distribution of powdered aggregate between water and low viscosity bitumen solution; a water displacement method in which a bitumen-coated aggregate mixture, preferably after curing, is exposed to a static water immersion test; an abrasion-displacement test in which a cured, bitumen-aggregate mixture is given a period of shaking after exposure to water; and a briquette-soaking evaluation made by simple exposure to water of a lightly compacted, bitumen-aggregate mixture of open grading with the time required for crumbling of the briquette being reported.

An article in Southeastern Road Builders (30) reports the use of radioactive calcium in the laboratory determination of asphalt stripping

from paving stone in which the results are measured with a Geiger counter. Two hundred grams of stone is wet with 0.1 percent solution of $CaCl_2$ containing calcium-45. The stone is dried. Half of the stone is coated with asphalt and the other half left uncoated as a blank. Each half is immersed in 100 ml water overnight. One cc aliquot of water from each is evaporated on a metal disc and checked with a Geiger counter. The counting rate is proportional to the surface of stone exposed to water. The percent of stripping is expressed as the ratio of counting rate of partially stripped and the counting rate of uncoated stone.

Stripping Test

Among the early tests for measuring the resistance of bituminous films on coated aggregates towards loosening and removal by the action of water or moisture was the visual stripping-resistance test. Where this test included agitation of the coated sample it was called a wash test. Dow (16) in 1936, used a wash test for differentiating between satisfactory and unsatisfactory aggregates for use in Colprovia mixes. This wash test has been described as follows: "A small batch of paving mixture is made up by the Colprovia process in the laboratory with the proper amount of asphalt; 50 grams of this loose mixture is placed in a 250 cc. Erlenmeyer flask with 100 cc. of distilled water and tightly corked. The flask and contents are shaken for different periods of time and examined after each period to note whether the water is cloudy, or if any of the mineral grains have lost their coating of oil and asphalt. The intervals of shaking are: 1, 3, 5, 10, 15, and 30 minutes. If a mixture stands washing through the 30 minute

period it is usually passed as satisfactory" (16).

A modification of earlier wash tests was used by Tyler (17) in his study, "Adhesion of Bituminous Films to Aggregates", in 1938. The original test calls for a bituminous mixture to be agitated in distilled water for varying periods of time. If no stripping occurs after the final washing, the material is declared satisfactory. In the modified method used by Tyler, the samples are cured for seven days, and the loss of volatile matter is determined each day. When the curing period is completed, the individual particles are separated by hand and immersed in a mason fruit jar containing 1,000 ml of distilled water. The jar is then placed in a rack contained in a modified Ro-Tap sieve-shaker and agitated for thirty minutes. After removal from the jar, the samples are graded according to visual inspection and count by three raters. The average of the three is reported.

This test determines whether a particular type of aggregate is hydrophilic or hydrophobic. If no stripping is observed after agitation, the stone is classified as hydrophobic and if stripped as hydrophilic, though these terms are relative and not absolute. Granite, quartz, and some cherts were found to be hydrophilic. The other type included dolomite, traprock, limestone and basalt (17).

Pauls and Rex (5) explain the serious disadvantages common to all stripping tests in their article, "A Test for Determining the Effect of Water on Bituminous Mixtures,". They are: "First, only one size fraction of the whole aggregate is usually selected for the test. Second, estimation of the extent of stripping is made by visual observation -- a method seriously lacking in precision. Third, results

of such tests give no indication of the actual degree of adhesion of the bituminous film to the aggregate particle. When the less viscous bituminous materials are used with certain aggregates, it has been observed that water will loosen or separate the film from the aggregate particle without, however, disturbing the continuity of the film. Failure of this type is not reflected in the results of the usual stripping test. Fourth, and most significant, there is no direct relation between the results obtained by any of the stripping tests and the effects that will be obtained when the complete bituminous mixture containing the aggregate in question is exposed to the action of water."

Stripping tests have considerable value, as, for example, in those cases as cited by Pauls and Goode (3): "1. Where an essentially one-size aggregate is being considered for use in surface treatment or macadam construction and where the value of the aggregate depends greatly on its film-retaining properties. 2. Where a coarse aggregate is being considered for use in graded mixtures in comparison with other aggregates, and in connection with material surveys in quickly rating the relative quality of the discovered materials."

Considerable work has been done in the development of a standardized stripping test for bitumen-aggregate mixtures (18) by the American Society for Testing Materials. The major effort has been concerned with the development of a method applicable to mixtures made with cold-application bitumens of the liquid cut-back type. These present a greater problem both in the field and in the laboratory testing than hot-application bitumens. Their work covered three phases: "1. A survey and review of published methods to determine the test conditions

most generally considered desirable. Based on this survey and the experience of the subcommittee members, a test procedure was agreed upon. 2. Numerous cooperative tests were made with different bitumens and aggregates to improve the test procedure and define more clearly the conditions necessary for best reproducibility. 3. Mechanical type, direct rating methods for measuring the degree of stripping have not yet been developed to the extent where they can be readily applied. Reliance must therefore be placed on visual estimation where reproducibility is mainly dependent on the ability of the rater. Thus, the last phase of the work has included a survey of the limitations of the visual estimation method."

The Static Immersion Stripping Resistance Test (18) described by A.S.T.M. in their report may be used provisionally and with due regard to the limitations on its precision.

Immersion-Compression Test

The Immersion-Compression Test grew out of a need for a more direct and quantitative evaluation of the effect of the presence of water-sensitive aggregates in a road surface than was given by available stripping tests. The test involves a comparison of the compressive strengths of molded cylindrical specimens of bituminous mixtures with the strengths of duplicate specimens that have undergone immersion in water for a definite period of time. The test gages the tendency of a mixture to strip by measuring the reduction in strength of the specimens caused by the loss in adhesion of the bituminous film to the aggregate particles. Krchma and Loomis (1) adopted the compressive-strength test from a technique used success-

fully in their laboratories as early as 1938. This method had definite advantage over the various stripping tests then in use. It provided a quantitative index of the damage caused by moisture and was made on the entire mixture as it might be prepared for use in the road rather than on the single-size fractions of aggregate that are used in the stripping tests.

"The compressive strength of a cylindrical specimen of a bituminous mixture without lateral support is dependent on the degree of cohesive strength of the mixture, as provided by the bituminous binder; and any damage to the mixture, such as stripping or reduction in the adhesion of the film to the surface of the aggregate particles, results in a measurable loss in strength of the specimen. For these reasons a compression test of laterally unsupported cylinders is believed to provide a satisfactory means of evaluating the damage caused by water" (19).

The test procedure suggested by Pauls and Rex (5) in their study, "A Test for Determining the Effect of Water on Bituminous Mixtures", is as follows: "1. The bituminous mixture for use in the test shall be composed of the aggregates, filler, and bituminous material in the proportions proposed for use in the actual construction. This is important, for it has been demonstrated that variations in aggregate, filler, or bituminous material result in corresponding differences in loss of stability. 2. Hot mixtures shall be molded immediately after mixing. All other mixtures shall be cured loose in air for 24 hours before molding. It has been found that such a curing period is necessary in order to obtain consistent results. 3. Cylindrical specimens four inches in diameter by four inches in height shall be molded under

a load of 3,000 pounds per square inch by the double plunger method. Other means of compaction that will produce equally satisfactory results may be used. At least six specimens shall be molded for each mixture to be tested. - - - 4. All molded specimens shall be cured for 24 hours in an oven maintained at a uniform temperature of 140°F. - - - 5. After oven curing, the specimens shall be allowed to cool to laboratory temperature, then weighed in air and water for density and volume determinations. 6. Three of the six specimens shall be tested in compression at room temperature after having been brought to a temperature of 77°F in an air bath. The other three specimens shall be submerged in water at a temperature of 77°F for a period of four days, after which they shall be removed from the water, weighed in air and water for moisture and volume determinations, and tested in compression. - - - 7. All specimens shall be tested in compression without lateral confinement, and at a rate of vertical deformation of 0.2 inch per minute."

Pauls and Goode (19) discuss the most suitable temperature and period of immersion for testing the hot mixtures. Temperatures of 77°, 100°, 120°, and 140°F, and periods of immersion of 1, 4, 14, and 35 days were investigated. The low temperature of 77°F did not show the significant differences between those mixtures that were known to have high resistance to the action of moisture and those known to have low resistance. At 100°F the results showed a somewhat greater differentiation between the several mixtures, but did not provide as positive a one as desirable. At 120°F the strength retention of the mixtures containing aggregates that were known to be superior was

consistently higher than that of the inferior mixture. Results of immersion tests at 140°F for one day were in close agreement with tests at 120°F for four days for several mixtures. Other mixtures showed a more rapid deterioration.

A standard method of test for "Effect of Water on Cohesion of Compacted Bituminous Mixtures" was adopted by the American Society for Testing Materials in 1954 (18). This test incorporates most of the test procedure suggested by Pauls and Rex (19) with some changes due to results of other investigations. The test is limited to penetration grade asphalts, has a different weathering period, and other prescribed conditions for the controlled water bath.

Sonic Test

The Sonic Test, using the method of finding the dynamic modulus of elasticity by sonic vibrations, has been used for some construction materials, particularly portland cement concrete, for several years. It is one of the most important tools for studying the durability of cement concrete, particularly when subjected to accelerated weathering tests. Among the pioneers of this method of test in the field of building materials were Grime (20), Eaton (21), and Powers (22), who experimented on such materials as tile, slate, paraffin wax, concrete, and many others. It has been only recently that this method of test was applied to the field of bituminous materials.

Bituminous paving mixtures, composed of aggregates bonded by a bituminous substance, at normal temperatures usually exhibit plastic characteristics. When the temperature is lowered, the material is affected in such a way that the lower the temperature, the more rigid

is the material. At lower temperatures, the material may act elastically. The greater the modulus of elasticity, the greater the stress set up in the material for a given change in length. A change in the physical properties of a compacted bitumen-aggregate mixture would be shown by a change in the modulus of elasticity. Where this change in physical properties in a bitumen-aggregate mixture is brought about by a loss in adhesive bond by water, we should be able to measure a change in the modulus of elasticity for the compacted specimen.

Bawa (11) in his sonic studies of bituminous mixtures, found that bitumen-aggregate beam specimens could be vibrated sonically, and in the course of his experiments found values for the moduli of elasticity and rigidity. Yong (12) in his study, "The Physical Significance of Sonic Tests on Bituminous Mixtures", concluded that the sonic method of test would be a useful tool in determining and following the relative deterioration of bitumen-aggregate mixtures when subjected to weathering tests.

Beam specimens used in the study conducted by Bawa (11) were twenty-four inches by four inches by three inches. Yong (12) in his study changed this beam size to twelve inches in length, two and one-half inches in width, and approximately two inches in depth. Both studies used a maximum aggregate size of one-half inch. Dynamic compaction was achieved by using a Marshall hammer acting upon an I-beam which in turn rested fully upon the broad face of the specimen. A total of seventy-five blows were applied, distributed evenly along the length of the I-beam, to the top and bottom faces of the specimen.

In testing, an audio oscillator was used to actuate the beam

specimens (12). Actual contact with the beam specimen was made by means of a driving mechanism using a crystal microphone connected to the output of the audio oscillator. Detection of the variable frequency of vibration of the beams was accomplished by using a crystal microphone which transmitted the frequency through an amplifier and finally to a cathode-ray oscilloscope.

The units functioned in the following manner (23): "The oscillator actuates the driving mechanism at any desired frequency within the range of the apparatus. The driving mechanism vibrates the specimen. The signal generated by the oscillator is fed into the resonance indicator and this results in - - - an amplitude indication on a cathode ray tube. The frequency at which the specimen is vibrated is transmitted to the resonance indicator through a pick-up device. This signal adds to the oscillator signal to raise the operating level of the resonance indicator. Since the electrical output of the pick-up increased with the mechanical input of the crystal, and the mechanical input is maximum when a specimen is vibrating at its fundamental frequency, - - - a cathode ray tube will register greatest amplitude, when the specimen is vibrating at its fundamental frequency. - - - The oscillator signal was fed to one set of plates on the tube and the amplified pick-up signal to the other set of plates. When these signals are of the same frequency and in phase, a Lissajous circle is seen on the tube screen."

When a beam was excited at its transverse frequency, the specimen had two nodal points which were 0.224L distant from the ends of the beam of length L. When such a state was achieved, the crystal pick-up was moved along the length of the beam and when a Lissajour circle was

formed on the tube screen, the frequencies of excitation and resonance were equal. If the points were truly nodal points there was zero amplitude of vibration at these points. Hence the gain on the Y set of plates was zero, and the trace on the tube screen showed a horizontal line with the pick-up at those points.

It should be realized at this point, that the theory of Sonic testing is based upon the concepts of elasticity and that this method of test is valid for elastic bodies. Bitumen-aggregate mixtures are not entirely elastic. The theory explaining how to obtain the modulus of elasticity from transverse vibrations in the beam specimens as explained by Yong (12) is found in Appendix B.

MATERIALS

Materials used in this study were two Indiana aggregates, Massachusetts rhyolite, and 85-100 penetration asphalt cement. Rhyolite was used as the hydrophilic aggregate for a comparison with the results obtained with the two Indiana aggregates, Greencastle limestone and Lafayette gravel. In this section is presented a description of the materials used in the study.

Aggregates

Crushed-limestone, used as the hydrophobic aggregate, was obtained from the Ohio and Indiana Stone Company located at Greencastle, Indiana. This aggregate was separated into the sieve fractions listed in Table 1 and recombined in the percentages listed. A graphical representation of the grading shown in Table 1 is presented in Figure 1. Sieving of the coarse portion of this aggregate was made with a "Gilson" mechanical sieving machine. Material passing the number 50 sieve was sieved on a "Ro-Tap" testing sieve shaker and U.S. Standard sieves. Specific gravity and absorption tests conforming to A.S.T.M. designations C 127-42 and C 128-42, were conducted on the aggregates, the results of which are presented in Table 3. The effective gravity of the aggregate was determined as outlined in "New Test Method for Direct Measurement of Maximum Density of Bituminous Mixtures" by James M. Rice (24).

Massachusetts rhyolite crushed stone, used as the hydrophilic aggregate, was obtained from the Rowe Contracting Company located at Malden, Massachusetts. The rhyolite rock received consisted of 100 percent passing the 3/8-inch square opening and 100 percent retained on the 1/4-inch square opening. Additional crushing of the rock produced

the sieve fractions passing the 1/4-inch opening. The aggregate was then separated into the sieve fractions listed in Table 1 and recombined in the percentages required for the Indiana AH Type B surface course gradation and the U.S. Army Corps of Engineers' surface course gradation (1/2-inch maximum) as shown in Table 1, Table 2, and Figure 1. Because no rhyolite passing the 1/2-inch sieve and retained on the 3/8-inch sieve was available, Greencastle limestone was used for this sieve fraction in the specimens made from the rhyolite to obtain the Indiana gradation and the Corps of Engineers' gradation.

An Indiana gravel aggregate, used for comparison with the other two aggregates, was obtained from the Western Indiana Gravel Company located at West Lafayette, Indiana. The aggregate was separated into the sieve fractions listed in Table 1 and recombined in the percentages listed with the exception of the fraction passing the No. 100 sieve and retained on the No. 200 sieve and the fraction passing the No. 200 sieve. These fractions were taken from the Greencastle limestone and follow the mineral filler requirements of the State Highway Commission of Indiana specifications. Results of specific gravity and absorption tests are presented in Table 3.

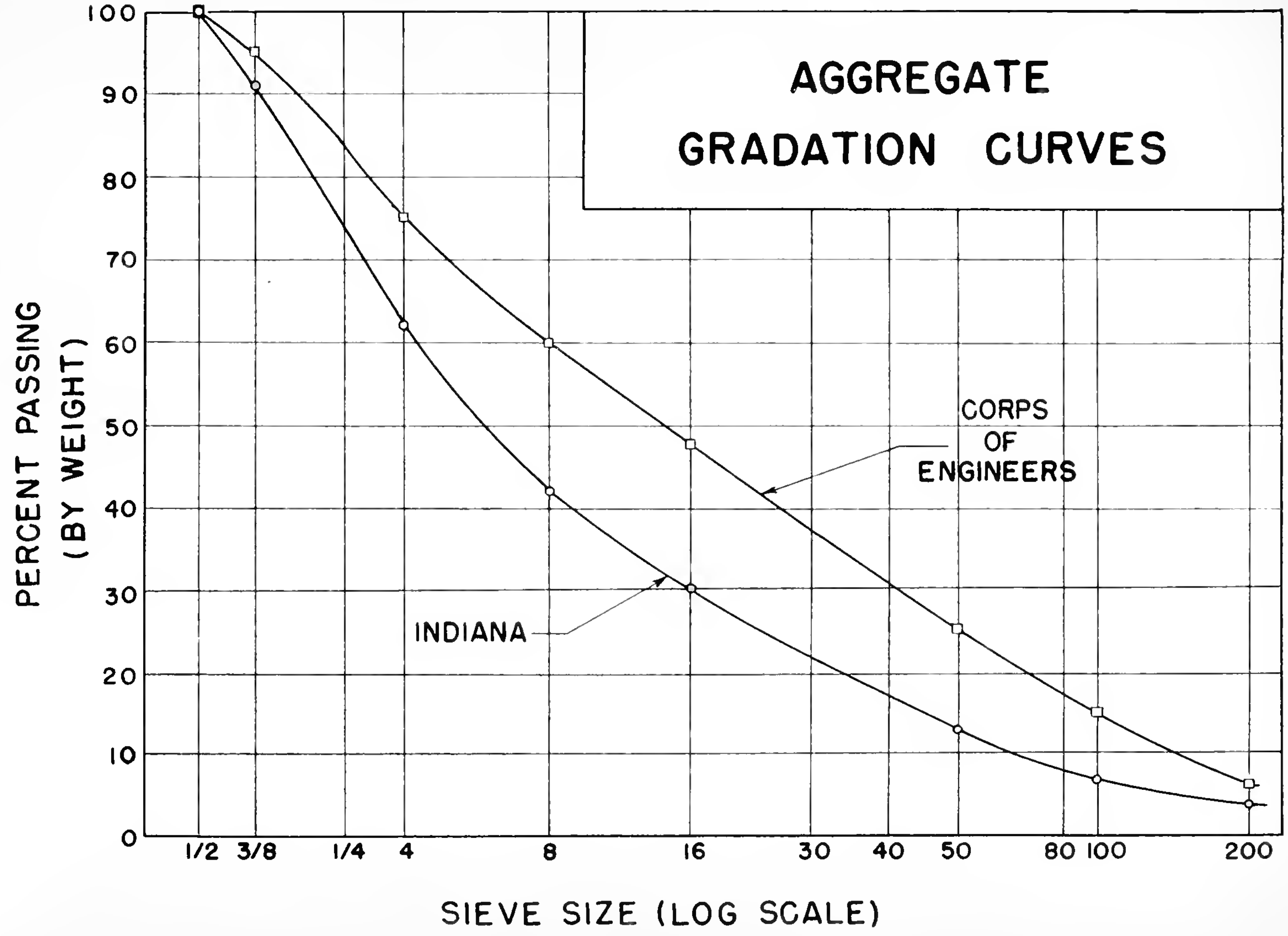
Table 1

Gradation for AH Type B

Hot Asphaltic Concrete Surface Course

State Highway Commission of Indiana

Passing Sieve	Retained Sieve	Percent by Weight
1/2 inch	3/8 inch	9
3/8 inch	No. 4	29
No. 4	No. 8	20
No. 8	No. 16	12
No. 16	No. 50	17
No. 50	No. 100	6
No. 100	No. 200	3
No. 200	- - -	4



AGGREGATE
GRADATION CURVES
PERCENT PASSING
(BY WEIGHT)
100
90
80
70
60
50
40
30
20
10
0
CORPS
OF
ENGINEERS
INDIANA
1/2
3/8
1/4
4
8
16
30
40
50
80
100
200
SIEVE SIZE (LOG SCALE)

FIG. 1

Table 2

Gradation for Bituminous-Aggregate Mix

Corps of Engineers' Surface Course

Passing Sieve	Retained Sieve	Percent by Weight
1/2 inch	3/8 inch	5
3/8 inch	No. 4	20
No. 4	No. 8	15
No. 8	No. 16	12
No. 16	No. 50	23
No. 50	No. 100	10
No. 100	No. 200	9
No. 200	- - -	6

Asphalt

Only one asphalt was used in this study since the lack of adhesive bond between a bitumen and an aggregate is characterized in most cases by the aggregate (7) (8). The 85-100 penetration asphalt was obtained from the Standard Oil Company, Whiting, Indiana. Penetration, specific gravity, solubility in carbon tetrachloride, and ductility tests conforming to A.S.T.M. designations D5-52, D70-52, D165-42, and D113-44 respectively, were conducted on the asphalt used in this study with the results presented in Table 4.

Table 3

Physical Properties of Aggregates

Aggregate	Bulk Sp Gr	App Sp Gr	Eff Sp Gr	Absorption, %
Massachusetts rhyolite	2.62	2.68	2.67	0.85
Greencastle limestone	2.63	2.71	2.67	1.39
Lafayette gravel	2.60	2.74	2.69	2.04

Table 4

Physical Properties of Asphalt

Test	85-100 Penetration
Penetration (100 gm. 5 secs. 77°F) 1/100 cm	91
Specific Gravity, 77°F	1.021
Solubility in CCl_4, %	99.94+
Ductility (77°F, 5 cm/sec) cm	150+

PROCEDURE

Three different types of tests were used in the course of this study. They included the Sonic Test, the A.S.T.M. Test D 1075-54 for "Effect of Water on Cohesion of Compacted Bituminous Mixtures", and the provisional A.S.T.M. "Static Immersion Stripping Resistance Test". The preparation of specimens and testing for the Sonic Test is explained in detail. The A.S.T.M. tests follow standard procedure with the exception of certain details changed to facilitate the preparation of specimens and the weathering procedure used on the specimens. Any changes from the standard procedures are described in their respective section.

Sonic Test

Beam specimens for the Sonic Test were molded using the three aggregates with the Indiana gradation shown in Table 1. Specimens containing rhyolite were also molded using the Corps of Engineers' gradation shown in Table 2. Asphalt content was 6 1/2 percent for all specimens. A detailed procedure on heating, mixing, and molding of the beam specimens is found in Appendix D.

The beam specimens measured twelve inches in length, two and one-half inches in width, and approximately two inches in height. These were prepared in a special mold (Fig. 2) using a static (Fig. 3) and roller (Fig. 4) type of compaction. A static load of 600 psi was first applied to top and bottom faces of the specimen, then ten passes with the rolling compaction at a load of 300 pounds per lineal inch was applied to the top face, and finally a static loading of 800 psi was applied to the top face. The rolling compaction was applied to the specimen through a rocker arm to simulate the compaction that an asphalt

pavement receives during actual field construction. Details on the roller-compactor attachment are given in Figures 22, 23, and 24 of Appendix D.

After compaction, the specimens were allowed to cool to room temperature before curing for a period of 24 hours in an oven at a temperature of 140°F. On removal from the curing oven, the specimens were cooled to room temperature and then their bulk specific gravities determined. Next the specimens were cooled for two hours in a water bath at 40°F prior to sonic testing. All specimens were placed on glass plates before curing and during water exposure to prevent breakage or distortion.

Sonic testing consisted of placing the beam specimen on the driving unit, actuating the driving unit with an audio oscillator, and determining the resonant frequency using a brush vibromike and cathode-ray oscillography (Fig. 5). Using the resonant frequency, dimensions of the beam, weight and density of the beam, and with Poisson's ratio assumed as 0.40, a modulus of elasticity was computed for the specimen. Sample calculations for the modulus of elasticity are given in Appendix C. Deterioration in the specimen was measured by the decrease in modulus of elasticity as the specimen was subjected to various degrees of water exposure.

The water exposure used in this study was continued immersion in water at a temperature of 140 ± 1.8°F for periods of 24 hours. Fresh, hot tap water with a pH of 7 was used for each period of immersion of 24 hours. Groups of four beams were used to obtain an average value of deterioration for each period. Readings for the resonant frequency were taken for exposure consisting of zero, one, three, five, seven, and nine periods.

The units for the Sonic Test (Fig. 6) functioned in the following manner: the audio oscillator actuated the beam specimen through the driving unit, at any desired frequency. The signal generated by the oscillator was fed into the cathode ray oscillograph through the pick-up device. This signal added to the oscillator signal to raise the operating level of the cathode ray oscillograph. Since the electrical output of the pick-up device increased with the mechanical input of the crystal, and the mechanical input was at a maximum when the specimen was vibrating at its fundamental frequency, the oscillograph registered maximum amplitude when the specimen was vibrating at its fundamental frequency. The oscillator signal was fed to the X set of plates on the cathode-ray tube and the pick-up signal to the Y set of plates. Hence when the signals were of the same frequency and in phase, a Lissajous circle was seen on the tube screen (Fig. 5). Data taken for the Sonic tests are presented in Tables 10, 11, 12, 13, and 14, in Appendix A.

Immersion-Compression Test

Cylindrical specimens used in the Immersion-Compression Test were made using the aggregate gradation shown in Table 1 for all three aggregates. The asphalt content followed the requirements of Indiana AH Type B surface course with 6 1/2 percent being used based on the total weight of the mixture. Heating and mixing of the asphalt and aggregate followed the same procedure used for the Sonic Test with the exception that two batches of 2,500 grams each were used for each 10-inch cylinder.

Specimens, measuring four inches in diameter and about four inches in height, were cut with a masonry saw from the ends of the 10-inch

cylinders (Fig. 7). Cylinders ten inches in height were molded rather than four inches in height because it was believed that 4-inch specimens sawed from the ends of 10-inch cylinders would have more identical densities than if individual 4-inch specimens were molded. A complete set of specimens were molded four inches in height and following all the requirements of the A.S.T.M. Test D 1075-54 "Standard Method of Test for Effect of Water on Cohesion of Compacted Bituminous Mixtures" as a check on results obtained using 4-inch high specimens cut from the ends of the 10-inch cylinders.

Compaction of the cylindrical specimens used the double-plunger method. An initial load of about 150 psi was applied to set the mixture against the sides of the mold and then the entire load of 3,000 psi was applied and maintained for two minutes.

On removal from the mold, all specimens were cooled to room temperature. The 10-inch cylinders were then frozen in preparation for cutting the 4-inch specimens off the ends with the masonry saw. After sawing and thawing, these specimens were placed with the molded 4-inch specimens in the curing oven for 24 hours at a temperature of 140°F. After curing, the bulk specific gravity was determined for each specimen and the specimens were divided into groups whose average specific gravities were equal or were as close to equal as possible. All specimens were placed on glass plates before curing and during water exposure to prevent breakage or distortion.

Prior to testing, specimens without exposure to water were stored in an air bath at 77 $\pm$ 1.8°F for not less than four hours. Specimens that had been subjected to water exposure were stored in a water bath at 77 $\pm$ 1.8°F for two hours before testing. The compressive strength

of the specimens was then determined in accordance with A.S.T.M. Method D 1074-52T.

The water exposure used on the Immersion-Compression specimens was the same as used for the Sonic Test beam specimens. It consisted of immersion in tap water with a pH of seven at a temperature of 140 ± 1.8°F for one, three, five, seven, and nine periods of 24 hours each. The set of molded 4-inch specimens was immersed in distilled water with a pH of five at a temperature of 140 ± 1.8°F for a period of one day. The immersion bath used for the molded 4-inch specimens met all the requirements of A.S.T.M. Method D 1075-54.

Stripping Test

The Stripping Test followed the Provisional A.S.T.M. "Static Immersion Stripping Resistance Test" procedure with the exception of several changes to permit taking of photos and continued immersion for the same periods used in the Sonic Test and the Immersion-Compression Test. Distilled water used had a pH of five. The aggregate and asphalt was mixed in accordance with the A.S.T.M. procedure.

Water immersion of the bitumen-coated aggregate was conducted by placement in the glass container and covering with distilled water. The coated aggregate was immersed in water at 140°F for one, three, five, seven, and nine periods of 24 hours each. Photos were taken of the immersed coated aggregate on completion of each period of exposure for all three aggregates used in this study.

On completion of the 9-days immersion, the evaluation of stripping resistance for the three aggregates was made in the following manner: Three observers made an estimate of the area of the aggregate surface

remaining coated for each aggregate, these estimates averaged and returned to the observers. Then each observer individually made his estimate from the photos of the percentage of the area of each aggregate remaining coated for one, three, five, and seven days immersion. These estimates by each observer for the respective period of immersion on each aggregate are given in Table 9.

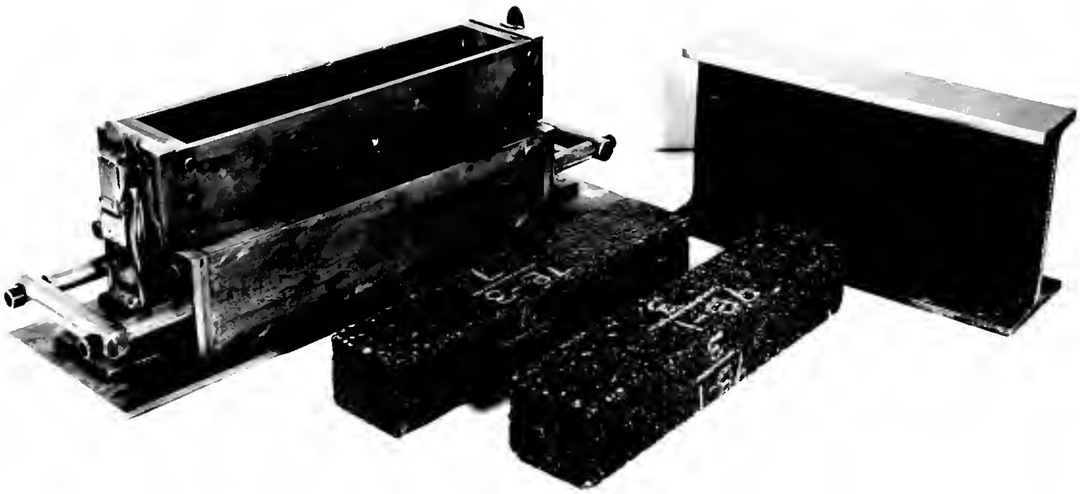


Fig. 2 - Beam Specimen Mold and Specimens

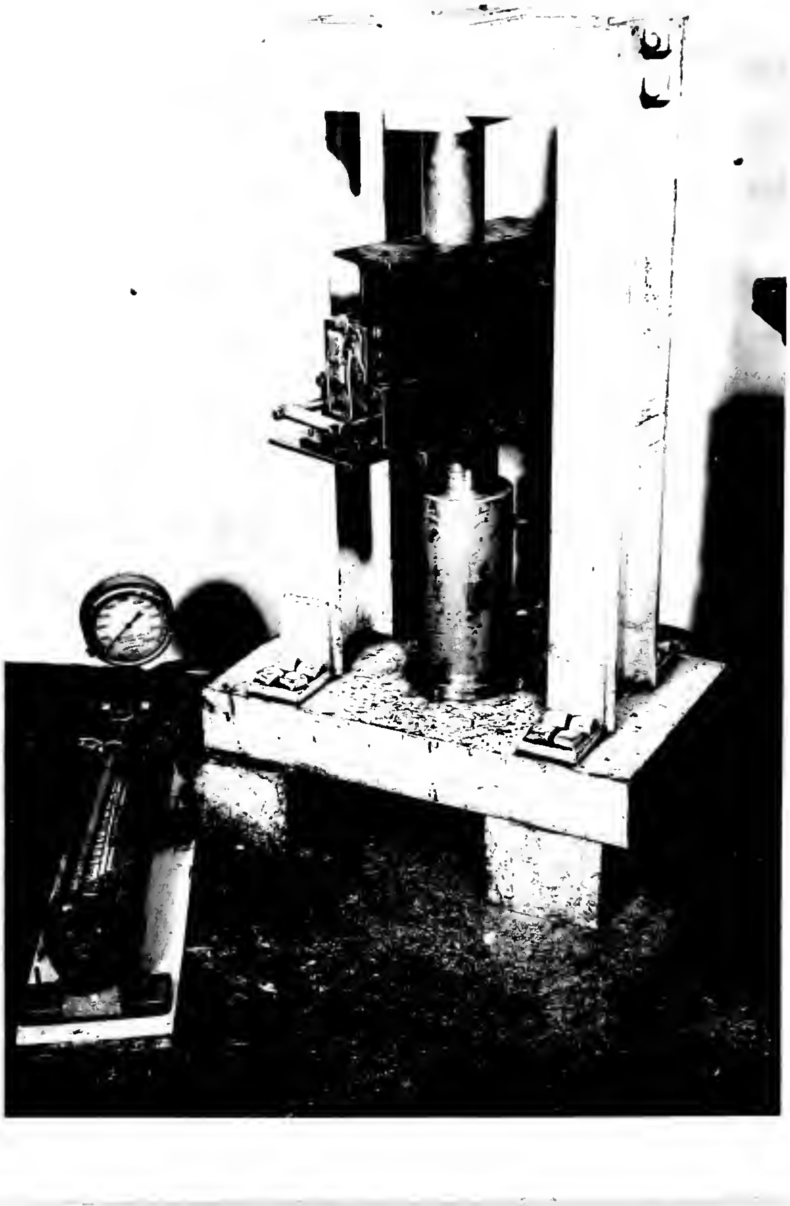


Fig. 3 - Static Load Applied to Beam Specimen

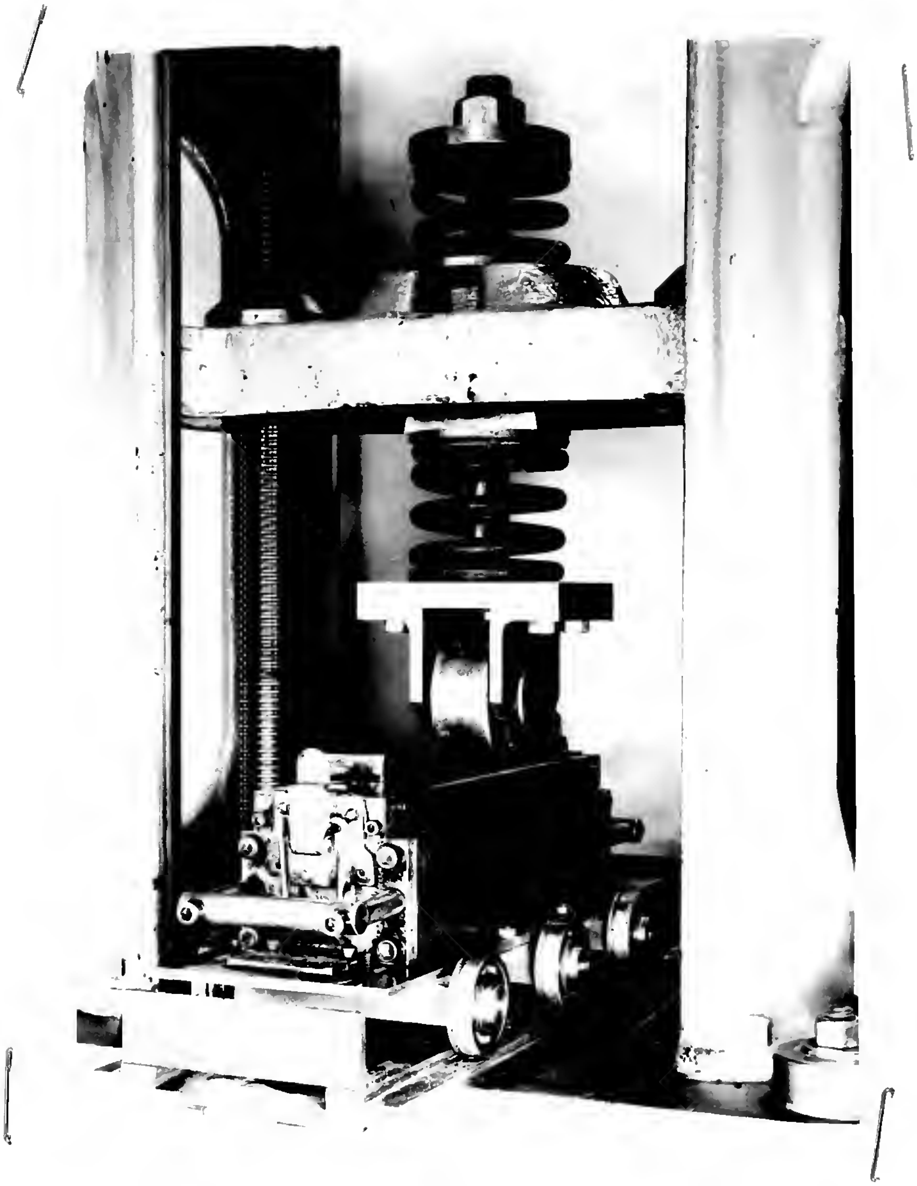


Fig. 4 - Rolling Action Applied to Beam Specimen

Fig. 5 - Sonic Test of Beam Specimen Showing Lissajous Circle on Oscillograph

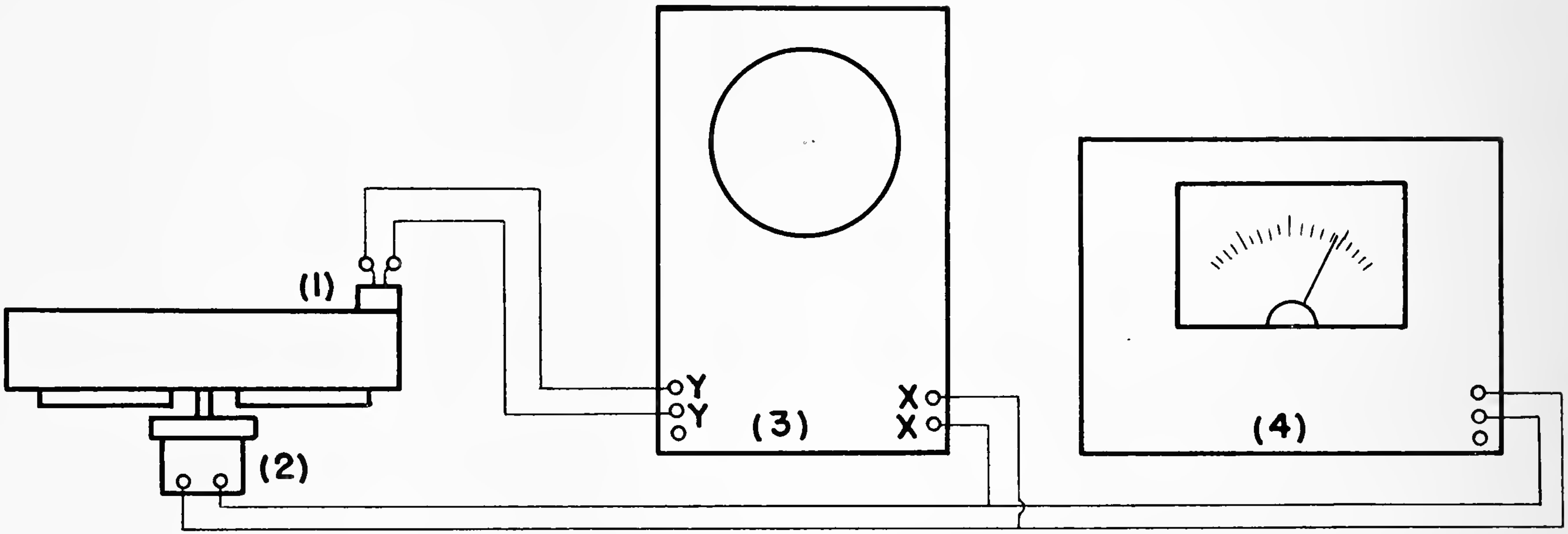


FIG. 6 SCHEMATIC SKETCH OF SONIC APPARATUS USED IN STUDY

(1) PICKUP, VM-1 BRUSH VIBROMIKE

(2) DRIVER, MODIFIED ST 104 JENSEN SPEAKER

(3) OSCILLOGRAPH, TYPE 304-A DUMONT CATHODE - RAY

(4) OSCILLATOR, MODEL 655 JACKSON AUDIO OSCILLATOR

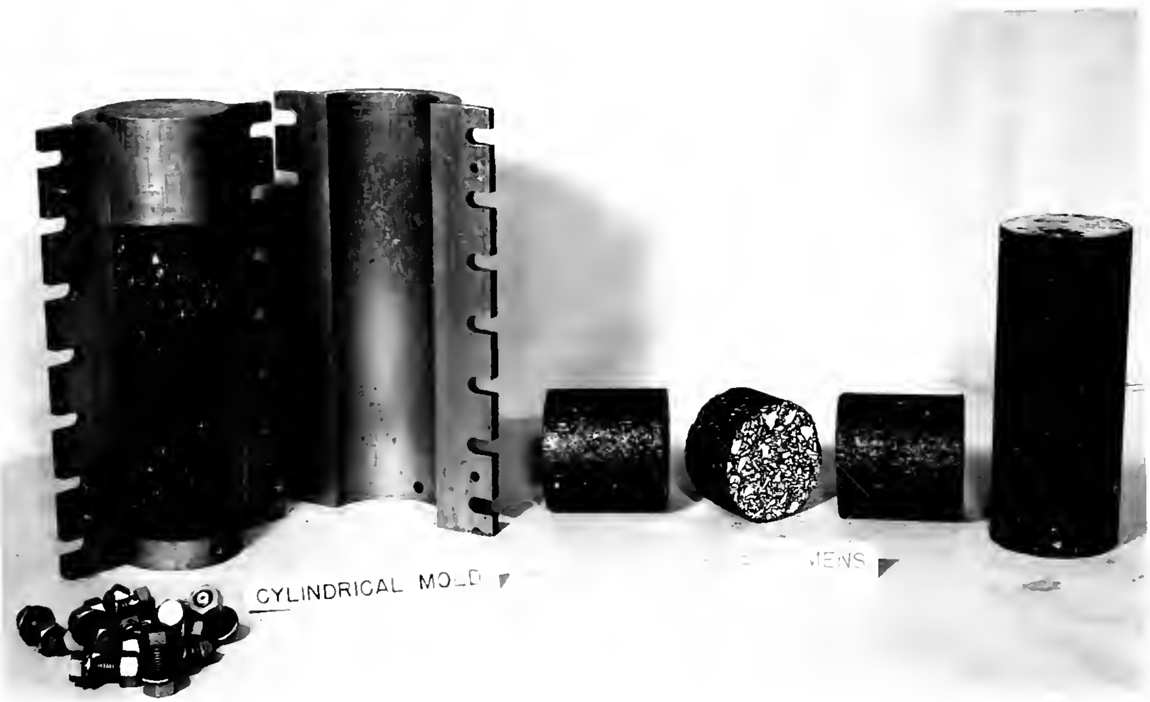


Fig. 7 - Cylindrical Mold and Specimens

RESULTS

The results of this study include data for the evaluation of stripping resistance in compacted bituminous mixtures obtained by the Sonic Test, the Immersion-Compression Test, and the Static Immersion Stripping Resistance Test. Three different aggregates, a gravel, a limestone, and a rhyolite, combined with one asphalt (85-100 penetration) were used to show different degrees of stripping when subjected to immersion in water under prescribed conditions of temperature and time. All three aggregates were processed to the same Indiana gradation and combined with 6 1/2 percent asphalt as described in the detailed procedures (Appendix D). Rhyolite was also processed to a Corps of Engineers' gradation and combined with 6 1/2 percent asphalt by weight to check the effect of gradation on the Sonic Test results. An asphalt bonding additive was used with the rhyolite in the Indiana gradation to find out what effect this would have on the results obtained by the Sonic Test. These data are presented in charts or tables in this section, while pertinent data on the specimens themselves are contained in Appendix A.

Sonic Test

The Sonic Test results for the three aggregates using the Indiana gradation are shown in Figure 8. The percent retained modulus of elasticity is plotted against days of immersion in water at 140°F. Numerical values plotted on this Figure are listed in Table 5 which includes the Sonic modulus values. Information about the specimens is listed in Tables 10, 11, 12, in Appendix A. Results showing the effect of a different gradation and the effect of the addition of an asphalt bonding additive are shown in Figure 9. Table 6 and part of Table 5 on the rhyolite stone

include the numerical values for Figure 9. Data about the specimens are listed in Tables 12, 13, and 14, in Appendix A.

Immersion-Compression Test

The Immersion-Compression Test results for the three aggregates using the Indiana gradation are shown in Figure 10. The percent total strength retained is plotted against days of immersion in water at 140°F. The numerical values plotted in Figure 10 are given in Table 7. Data about the Immersion-Compression Test specimens are listed in Tables 15, 16, and 17, in Appendix A. The A.S.T.M. Standard Method of Test for Effect of Water on Cohesion of Compacted Bituminous Mixtures was applied to all three aggregates as a check on results obtained using 4-inch specimens sawed from each end of molded 10-inch cylinders. Data on specimens prepared and tested by the standard method are listed in Table 8.

Stripping Test

Results from the Static Immersion Stripping Resistance Test using the three different aggregates are shown in Figure 11. The percent area aggregate remaining coated is plotted against days of immersion in water at 140°F. Numerical values for Figure 11 are listed in Table 9 including individual estimates by the observers. Photographs showing the results of zero, one, and seven days immersion in water at 140°F for the three aggregates are included as Figures 12 through 20. These photographs were taken with the aggregate and asphalt covered with water in ordinary room light in an attempt to reduce the reflective glare from the asphalt. The three photographs selected for each aggregate illustrate the degree of stripping that takes place in this test.

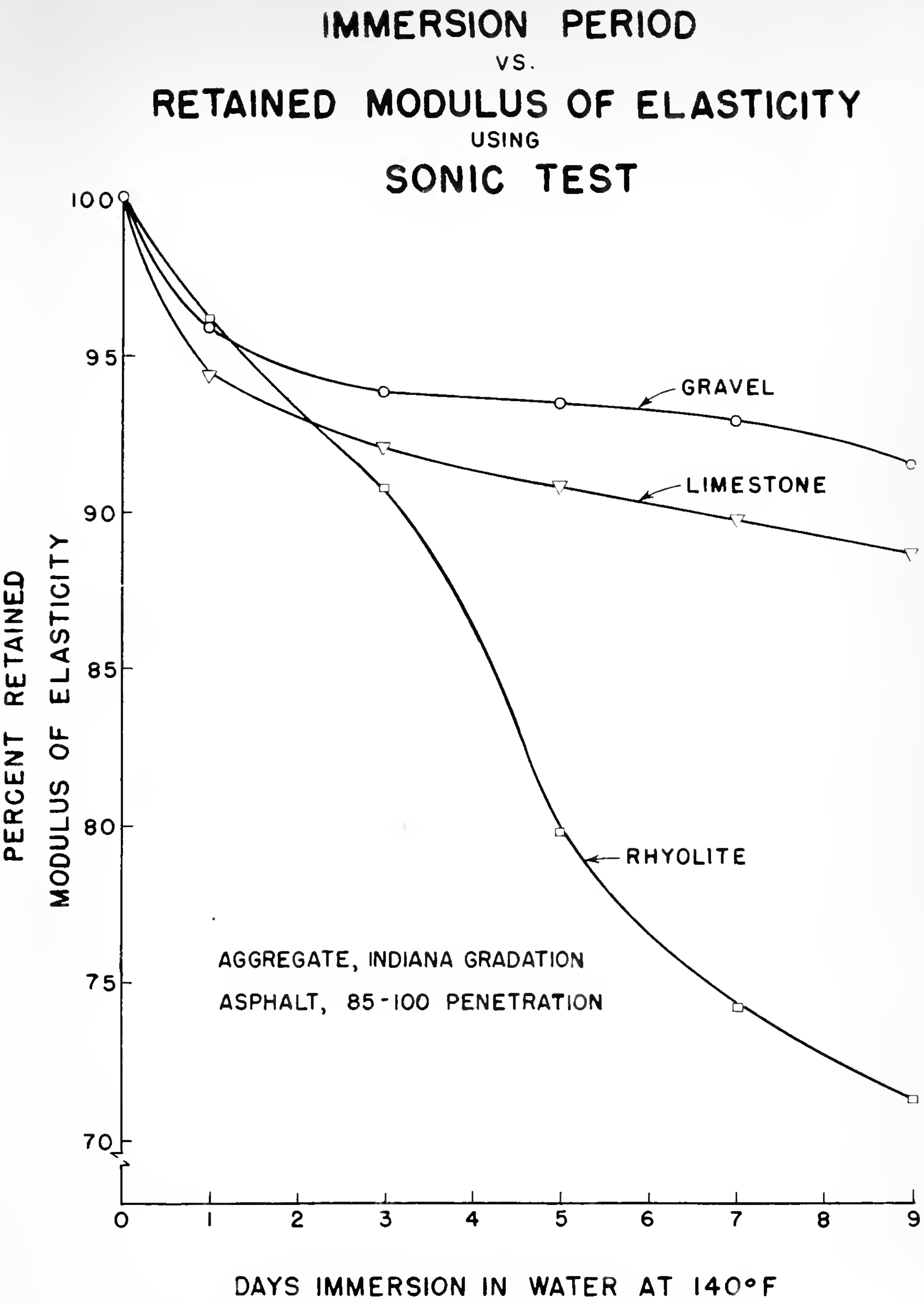

IMMERSION PERIOD
VS.
RETAINED MODULUS OF ELASTICITY
USING
SONIC TEST
PERCENT RETAINED
MODULUS OF ELASTICITY
100
95
90
85
80
75
70
GRAVEL
LIMESTONE
RHYOLITE
AGGREGATE, INDIANA GRADATION
ASPHALT, 85-100 PENETRATION
0
1
2
3
4
5
6
7
8
9
DAYS IMMERSION IN WATER AT 140°F

FIG. 8

Table 5

Sonic Test Results

Indiana AH Type B Surface Course

Days Immersion in Water at 140°F	Av of 4 beams, Sonic Modulus x 10^6 psi	% Retained Sonic Modulus
	Lafayette Gravel	
0	2.95	100.0
1	2.83	95.9
3	2.77	93.8
5	2.76	93.5
7	2.74	92.9
9	2.70	91.5
	Greencastle Limestone	
0	3.29	100.0
1	3.10	94.3
3	3.03	92.1
5	2.99	90.8
7	2.95	89.7
9	2.92	88.7
	Massachusetts Rhyolite	
0	2.09	100.0
1	2.01	96.2
3	1.90	90.8
5	1.67	79.8
7	1.55	74.2
9	1.49	71.3

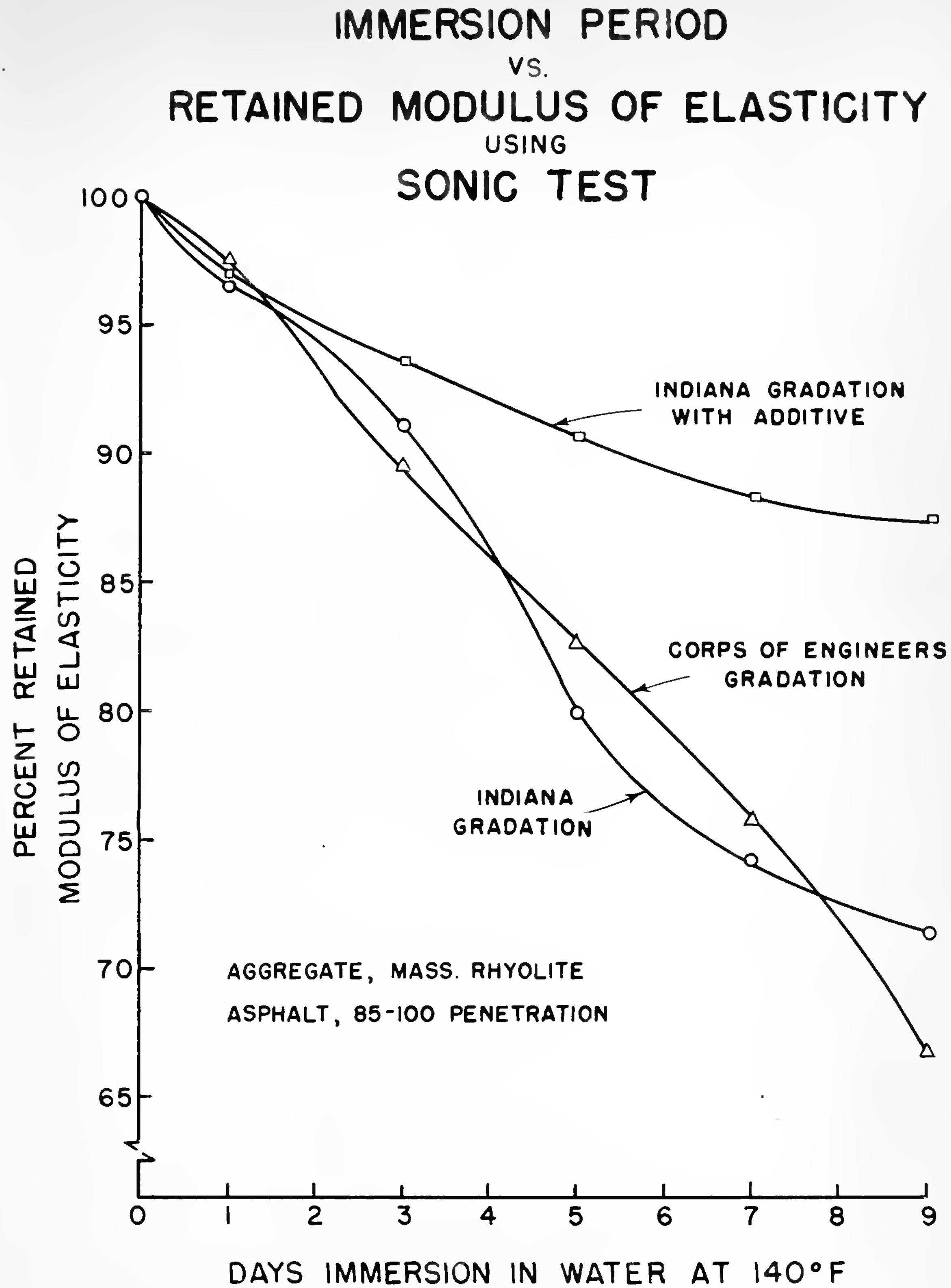

IMMERSION PERIOD
VS.
RETAINED MODULUS OF ELASTICITY
USING
SONIC TEST
PERCENT RETAINED
MODULUS OF ELASTICITY
100
95
90
85
80
75
70
65
INDIANA GRADATION
WITH ADDITIVE
CORPS OF ENGINEERS
GRADATION
INDIANA
GRADATION
AGGREGATE, MASS. RHYOLITE
ASPHALT, 85-100 PENETRATION
0
1
2
3
4
5
6
7
8
9
DAYS IMMERSION IN WATER AT 140°F

FIG. 9

Table 6

Sonic Test Results

Massachusetts Rhyolite

Days Immersion in Water at 140°F	Av Sonic Modulus x 10^6 psi, 4 beams	% Retained Sonic Modulus
Indiana AH Type B Surface Course with an Asphalt Additive		
0	2.10	100.0
1	2.03	96.7
3	1.96	93.3
5	1.90	90.4
7	1.85	88.1
9	1.83	87.2
Corps of Engineers' Surface Course		
0	2.80	100.0
1	2.72	97.2
3	2.43	89.2
5	2.31	82.5
7	2.12	75.7
9	1.87	66.8

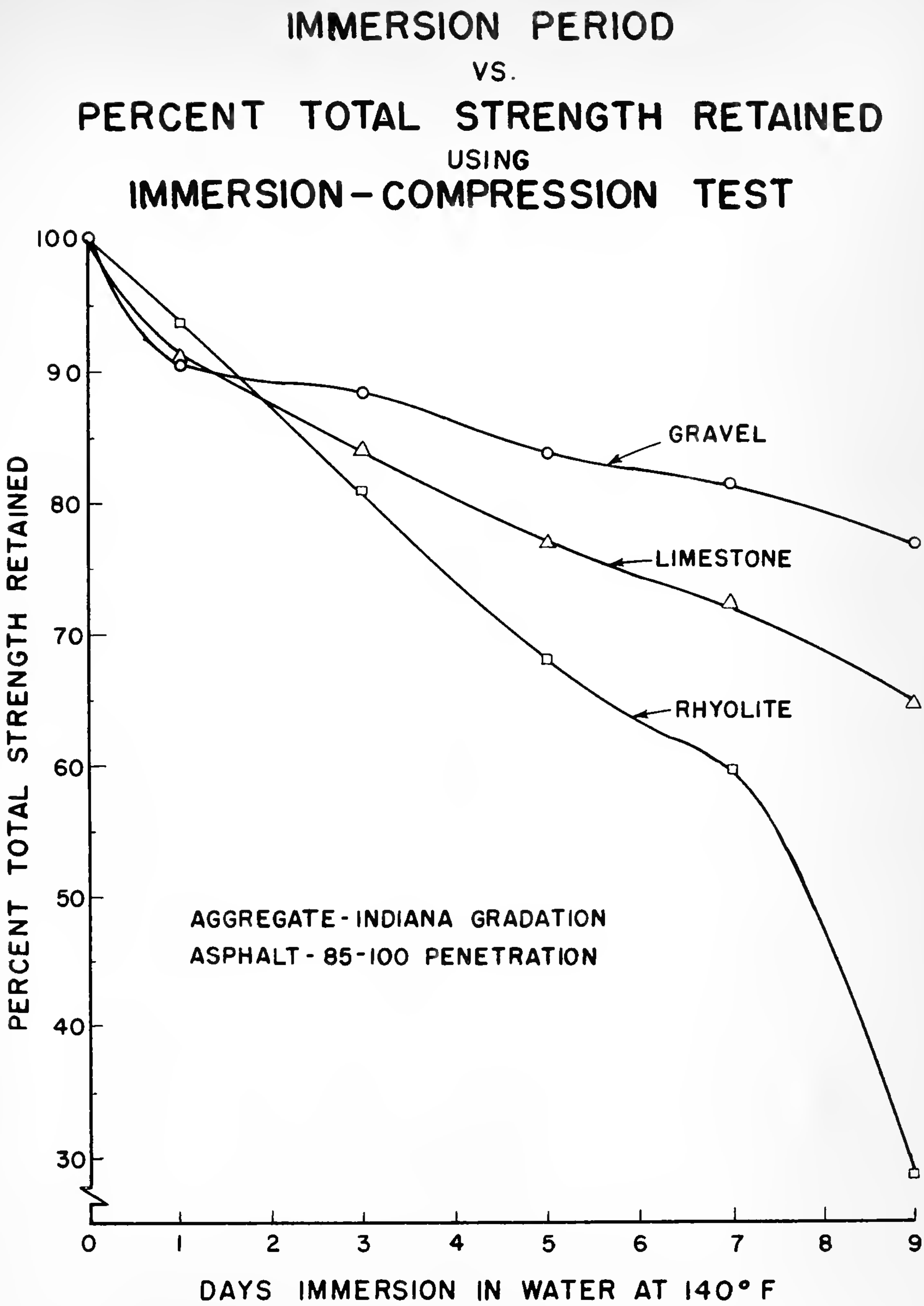

IMMERSION PERIOD
VS.
PERCENT TOTAL STRENGTH RETAINED
USING
IMMERSION-COMPRESSION TEST
PERCENT TOTAL STRENGTH RETAINED
100
90
80
70
60
50
40
30
GRAVEL
LIMESTONE
RHYOLITE
AGGREGATE - INDIANA GRADATION
ASPHALT - 85-100 PENETRATION
0
1
2
3
4
5
6
7
8
9
DAYS IMMERSION IN WATER AT 140° F

FIG. 10

Table 7

Immersion-Compression Test Results

Indiana AH Type B Surface Course

Days Immersion in Water at 140°F	Av Comp Strength 3 Specimens, lb	% Retained Strength
	Lafayette Gravel	
0	2958	100.0
1	2688	90.3
3	2614	88.3
5	2468	83.5
7	2418	81.7
9	2277	76.9
	Greencastle Limestone	
0	4346	100.0
1	3947	90.8
3	3654	84.0
5	3338	76.8
7	3122	72.0
9	2797	64.3
	Massachusetts Rhyolite	
0	3236	100.0
1	3020	93.3
3	2615	80.8
5	2197	67.8
7	1928	59.6
9	922	28.5

Table 8

Immersion-Compression Test Results

A.S.T.M. Test D1075-54

Indiana AH Type B Surface Course

Spec #	Bulk Sp Gr	Av Bulk Sp Gr	Voids by App Sp Gr	Voids by Eff Sp Gr	Days Immersion at 140°F	Comp Strength, lb	Av Comp Strength, lb	% Ret Strength
Lafayette Gravel								
2	2.38		3.4	2.1	0	2615		
4	2.36	2.36	3.2	1.9	0	2970	2762	100.0
6	2.38		3.1	1.6	0	2700		
1	2.38		3.4	2.1	1	2505		
3	2.35	2.38	3.4	2.1	1	2885	2777	100.3
5	2.38		3.3	2.0	1	2940		
Greencastle Limestone								
2	2.40		1.7	0.7	0	4473		
5	2.41	2.40	1.2	0.3	0	5050	5141	100.0
6	2.40		1.6	0.6	0	6000		
1	2.40		1.5	0.5	1	4165		
3	2.40	2.40	1.5	0.5	1	4510	4325	84.2
4	2.40		1.5	0.6	1	4300		

(Table continued on next page)

Table 8 (Cont.)

Immersion-Compression Test Results

A.S.T.M. Test D1075-54

Indiana AH Type B Surface Course

Spec #	Bulk Sp Gr	Av Bulk Sp Gr	Voids by App Sp Gr	Voids By Eff Sp Gr	Days Immersion at 140°F	Comp Strength, lb	Av Comp Strength, lb	% Ret Strength
Massachusetts Rhyolite								
1	2.22		7.6	7.5	0	3400		
5	2.22	2.22	7.0	6.9	0	3340	3321	100.0
6	2.23		7.2	7.2	0	3222		
2	2.22		7.4	7.4	1	2790		
3	2.23	2.23	7.3	7.3	1	2890	2785	83.8
4	2.23		7.5	7.5	1	2675		

IMMERSION PERIOD
VS.
PERCENT AREA AGGREGATE REMAINING COATED
USING
STRIPPING RESISTANCE TEST

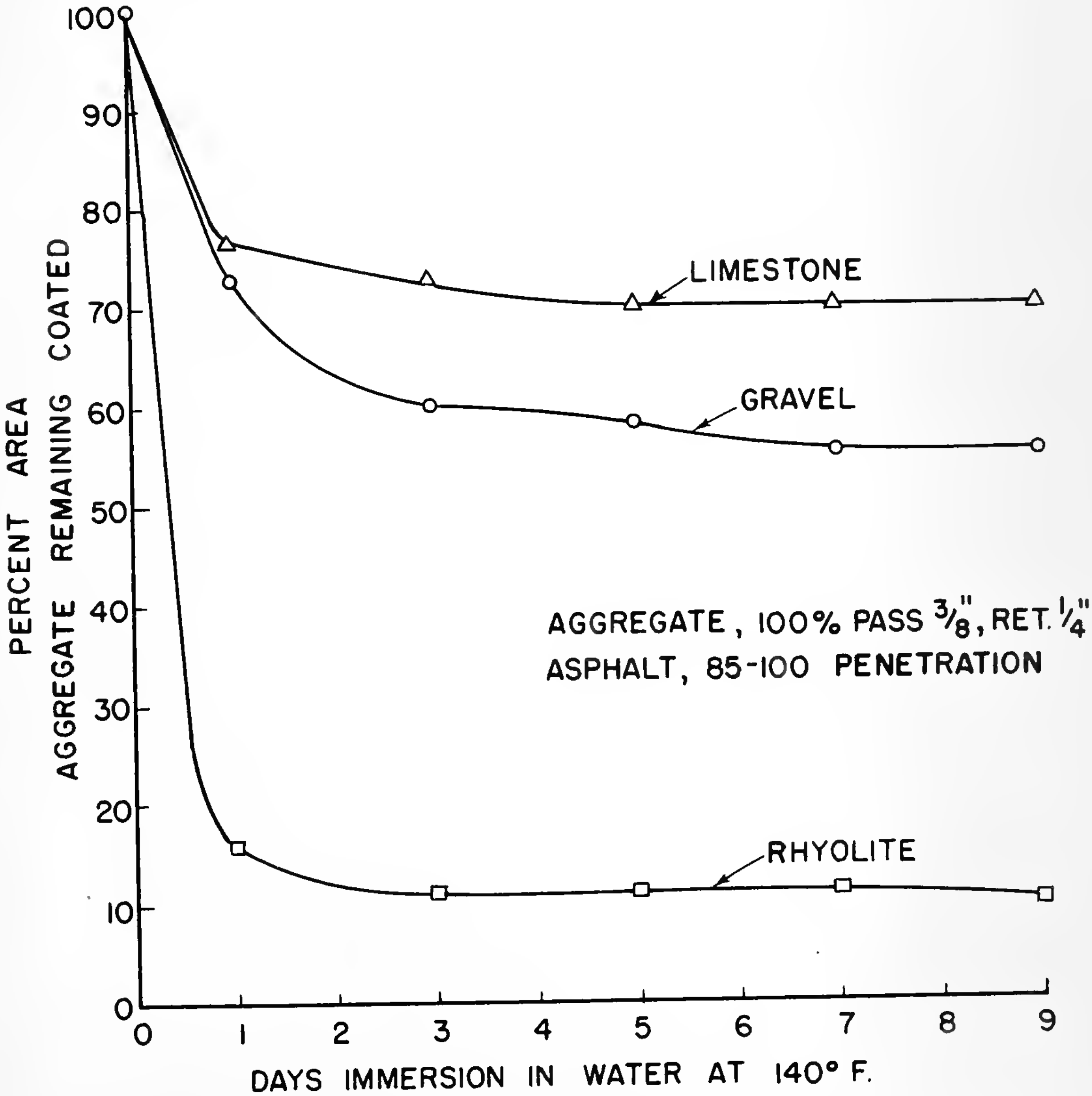


FIG. 11

Table 9

Static Immersion Stripping Resistance Test Results

Days Immersion at 140°F	Estimated Percent Area Aggregate Remaining Coated			
	1st Observer	2nd Observer	3rd Observer	Average of 3 Observers
Lafayette Gravel				
0	100	100	100	100
1	70	80	70	73
3	65	60	55	60
5	60	60	55	58
7	55	55	55	55
9	55	55	55	55
Greencastle Limestone				
0	100	100	100	100
1	80	80	70	77
3	75	75	70	73
5	70	70	70	70
7	70	70	70	70
9	70	70	70	70
Massachusetts Rhyolite				
0	100	100	100	100
1	20	20	10	17
3	10	15	10	12
5	10	15	10	12
7	10	15	10	12
9	10	10	10	10

Fig. 12 - Asphalt-Coated Gravel Before Immersion in Water

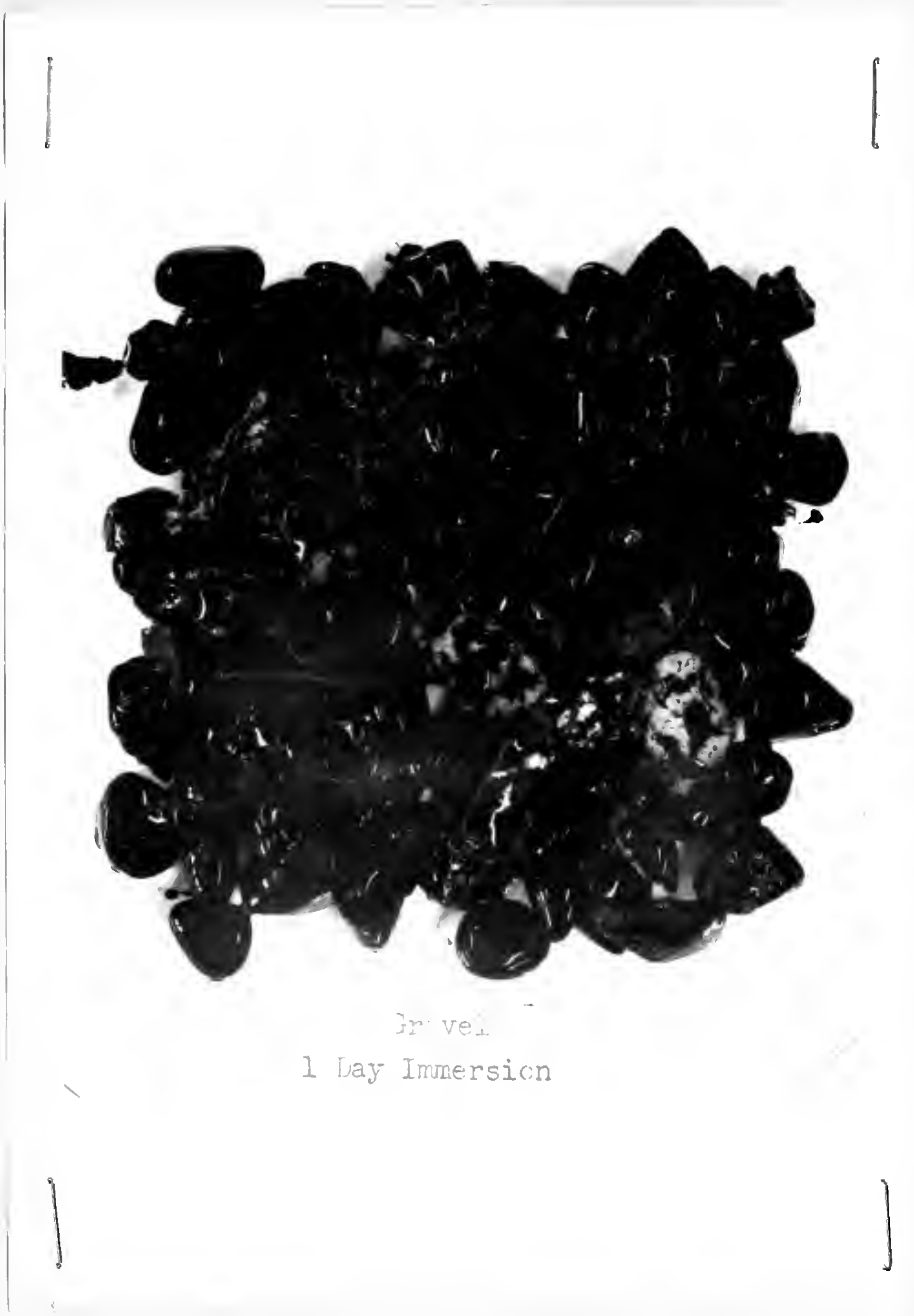


Fig. 13 - Asphalt-Coated Gravel After One Day Immersion In Water at 140°F

Fig. 14 - Asphalt-Coated Gravel After Seven Days Immersion In Water at 140°F

Fig. 15 - Asphalt-Coated Limestone Before Immersion In Water

Limestone
1 Day Immersion

Fig. 16 - Asphalt-Coated Limestone After One Day Immersion In Water at 140°F

Fig. 17 - Asphalt-Coated Limestone After Seven Days Immersion In Water at 140°F

Fig. 18 - Asphalt-Coated Rhyolite Before Immersion In Water

Fig. 19 - Asphalt-Coated Rhyolite After One Day Immersion In Water at 140°F

Fig. 20 - Asphalt-Coated Rhyolite After Seven Days Immersion In Water at 140°F

DISCUSSION OF RESULTS

This discussion (a) describes the results obtained using the Sonic Test, (b) compares them with results using the Immersion-Compression Test, (c) compares them with results using the Static Immersion Stripping Resistance Test, and (d) discusses the advantages of the Sonic Test with respect to other tests.

Sonic Test

The stripping qualities of the aggregates as reflected in the Indiana AH Type B surface course mixtures by means of the Sonic Test are shown graphically in Figure 8 on the basis of percent retained modulus of elasticity versus days immersion in water at 140°F. Plotted results for the mixtures in which the three aggregates were used show a decrease in retained modulus of elasticity throughout the period of immersion. Initially this decrease is rapid for all three mixtures. After about one day of immersion, the slopes of the curves for the gravel and limestone mixtures decrease fairly consistently at a lesser slope with time of exposure while the rhyolite curve continues at about the same slope for the additional periods of immersion. With the more dense Corps of Engineers' gradation, about the same decrease in retained modulus of elasticity was obtained for the rhyolite aggregate (Fig. 9) as is shown with the Indiana gradation.

A lithological count of the gravel reveals that it contains about 53 percent limestone. Since all the material passing the Number 100 sieve used in the gravel specimens was limestone, the final limestone content of the gravel specimens was about 57 percent. This would indicate why

results obtained for the gravel are more nearly like those obtained for the limestone than those obtained for the rhyolite.

On completion of one day immersion, the mixture containing hydrophilic rhyolite has a higher retained modulus of elasticity than either the gravel or the limestone mixtures (Fig. 8). This would indicate that the true stripping qualities of the aggregates are not revealed by the Sonic Test until after one day immersion with the gradation, asphalt content, density, and exposure conditions used in this study. Continued immersion results in complete failure of the specimens as shown in Figure 21.

An indication of the effect of gradation on results for the Sonic Test is shown in Figure 9. The average values for one group of four specimens made with the Indiana gradation is compared to the average values for another group of four specimens made with the Corps of Engineers' gradation, other conditions remaining the same. Plotted results of both groups follow about the same general slope.

The addition of an asphalt bonding additive to the Indiana surface course mixture using rhyolite aggregate resulted in a much higher percent retained modulus of elasticity at all periods of immersion after one day than without any additive as shown in Figure 9. The asphalt bonding additive used with the rhyolite improved its stripping qualities to the extent where it was comparable to the limestone with no additive. Again, as was the case without additive, the stripping qualities of the rhyolite were not shown until after more than one day immersion.

An examination of the fundamental frequency and sonic modulus data for duplicate beam specimens included in Tables 10, 11, 12, 13, and 14,

Appendix A, reveals that substantially the same results were obtained for duplicate tests in each case. An almost identical result would have been obtained in any case if only one beam specimen had been used to obtain the test result rather than the average of four such specimens. This indicates excellent reproducibility for the Sonic Test as used in this study. This fact, coupled with the fact that the Sonic Test is a non-destructive one, makes it possible to obtain a maximum of information with a minimum number of specimens when the Sonic Test is used.

Comparison of Sonic Test With Immersion-Compression Test

The stripping qualities of the aggregates as determined by the Immersion-Compression Test are shown graphically in Figure 10 on the basis of percent total strength retained versus days immersion in water at 140°F. After one day immersion, the stripping qualities of the rhyolite are not established. This is in agreement with the Sonic Test results (Fig. 8). Two days or more are required for either test to show the strongly hydrophilic character of the rhyolite. Continued immersion of the gravel and limestone specimens showed a smaller change in percent strength than is shown by the rhyolite specimens. For mixtures containing the same aggregates, the Sonic Test showed, qualitatively, a similar drop in percent retained modulus of elasticity as shown by the drop in percent total strength retained in the Immersion-Compression Test. Continued immersion of the Immersion-Compression rhyolite specimens resulted in complete failure as shown in Figure 22 in approximately ten days. The decrease in percent retained modulus of elasticity for all aggregate mixtures using the Sonic Test numerically was not as great as the decrease

in percent total strength obtained for similar mixtures tested by the Immersion-Compression Test.

Some specimens used in the Immersion-Compression Test showed a higher retained strength after three days immersion than some other specimens did after one day immersion (Table 15, Appendix A). In an attempt to find out if the method of molding 10-inch cylinders and sawing a 4-inch specimen from each end was the reason for these discrepancies, a complete set of six specimens was prepared for each aggregate following the requirements for the A.S.T.M. Test D1074-54. The results of tests on these molded 4-inch specimens showed the same inconsistencies in total retained strength between specimens subjected to no immersion and one day immersion (Table 8) as was obtained using 4-inch specimens sawed from the ends of 10-inch cylinders.

An examination of the compressive strength data in Tables 15, 16, and 17, Appendix A, for duplicate Immersion-Compression Test specimens reveals that it was difficult to obtain consistent results and accounts for the fact that the standard test procedure requires the molding of six specimens of any one mixture for test. This is in direct contrast to the Sonic Test.

Comparison of Sonic Test With Visual Stripping Test

The stripping qualities of the three aggregates using the Static Immersion Stripping Test are shown graphically in Figure 11 on the basis of percent area aggregate remaining coated versus days immersion in water at 140°F. All three coated aggregates show a sharp decrease in percent area aggregate remaining coated within the first day of immersion. After

one day immersion the area remaining coated decreased very little from the one-day value in any case. The hydrophilic nature of the rhyolite is shown by a much greater initial drop in percent area aggregate remaining coated than occurred with either the gravel or limestone. The limestone showed the more area remaining coated when compared to the gravel by the Visual Stripping Test. The gradation, 100 percent passing the 3/8-inch sieve and retained on the 1/4-inch sieve, and uncompacted materials used in the Visual Stripping Test account for the difference in results as obtained by the Sonic Test and the Immersion-Compression Test. Photographs taken for zero, one, and seven days immersion for each aggregate illustrate the Visual Stripping Test results (Figures 12 through 20).

Advantages of Sonic Test

In this study, the comparison of results from the three different methods of tests illustrates definite advantages for the Sonic Test in conducting a check on the stripping qualities of a particular aggregate and asphalt.

First, the Sonic Test is conducted on the beam specimens molded from the bituminous mixture as it would be used in the field. This bituminous mixture has the same aggregate, filler, and bituminous material in the proportions used for actual construction and is compacted in a manner designed to simulate field compaction. It would be expected that the test would be sensitive to variations in the aggregate, filler, asphalt bonding additive, or other factors.

Second, the beam specimens can be used for repeated exposure cycles, the same beam being tested on completion of each cycle. This procedure

eliminates errors caused by duplicate specimens having different characteristics as experienced in the Immersion-Compression Test. The deterioration of the same specimen is observed on completion of each cycle of exposure. With no need for a large number of duplicate specimens, this saves time and work normally involved in preparing the additional specimens.

Third, a quantitative measurement of loss in adhesion or stripping is obtained for each specimen based on the actual deterioration of the compacted bituminous mixture. The numerical values are unaffected by the personal factor involved in the estimation systems as used in several stripping tests.

Fig. 21 - Failure of a Rhyolite Beam Specimen Because of Stripping

Fig. 22 - Failure of a Rhyolite Immersion-Compression Specimen Because of Stripping

CONCLUSIONS

This laboratory study was initiated for the purpose of determining the usefulness of the Sonic Test in evaluating the stripping qualities of compacted bitumen-aggregate mixtures containing penetration grade asphalts. Sonic Test results are compared with the results of two other tests using three different aggregates, one asphalt, two gradations, and with other conditions as much alike as possible. With this in mind, and within the limits of the materials and methods employed, the following conclusions seem justified:

1. The Sonic Test gave results that revealed the stripping qualities of the aggregates employed as well as or better than either the Immersion-Compression Test or the Visual Stripping Resistance Test. Since specimens for the Sonic Test contained materials of the same kind, gradation, and proportions compacted in a similar manner as would be used in actual field construction, the Sonic Test has inherent advantages over both the Immersion-Compression Test and the Visual Stripping Test.

2. The Sonic Test permitted observation of progressive stripping on the same beam specimens. In the Immersion-Compression Test additional specimens are required in order to observe deterioration of the specimens at various periods of exposure. Use of these additional specimens for the Immersion-Compression Test brought inconsistent results, some specimens showing a greater compressive strength for the later stages of exposure than other specimens did for less exposure.

3. Use of the Sonic Test permits a comparison of stripping qualities for different aggregates and asphalts using beam specimens molded follow-

ing the same procedure and exposed to the same exposure conditions for various periods of exposure. One group of four specimens will more than satisfy specimen requirements for each mixture. By this method, an aggregate and asphalt with a known record of field performance may be compared with another aggregate and asphalt with an unknown record of stripping performance.

4. The Sonic Test appears to have application in evaluating whether the stripping tendency of a specific aggregate or bitumen might be improved by the use of anti-stripping additives. On this basis it seems feasible to use the Sonic Test in checking the effectiveness of different anti-stripping additives in reducing stripping in a particular bituminous mixture.

5. The compaction procedure used in molding the beam specimens gave densities comparable to those densities obtained using the double-plunger method. The rolling action applied to the beam specimens during molding would seem to give particle orientation similar to that obtained in field construction following rolling. Since double-plunger compaction as used in these tests is known to produce densities comparable to that obtained in field construction, and since the Sonic Test evaluation of stripping tendencies for the three aggregates used in this study are thought to be realistic, it is indicated that the Sonic Test might produce laboratory results that would correlate well with results in the field.

SUGGESTIONS FOR FURTHER WORK

The results of this study and previous work on the Sonic Test by Yong (12), Shupe and Taylor (29), suggest its application to correlation of field data with laboratory data by cutting beams from the road surface and testing them in the laboratory. This method of using the test may be applicable not only to the evaluation of the stripping problem but also the general durability problem including freezing and thawing, and may possibly offer a new basis for designing asphaltic concrete, especially durability design.

There is a need for a good test to evaluate stripping resistance of cold mixes. Based on work done by Pauls and Rex (5) with the Immersion-Compression Test, the Sonic Test may have application to cold mixes.

BIBLIOGRAPHY

1. Krchma, L. C., and Loomis, R. J., "Bituminous-Aggregate Water Resistance Studies," Proceedings, Association of Asphalt Paving Technologists, Vol. 15, December, 1943.

2. Public Roads Administration, "Principles of Highway Construction as Applied to Airports, Flight Strips, and other Landing Areas for Aircraft," June, 1943.

3. Pauls, J. T., and Goode, J. F., "Application and Present Status of the Immersion-Compression Test," Proceedings, Association of Asphalt Paving Technologists, Vol. 16, February, 1947.

4. Sanderson, Frederick C., "Methylchlorosilanes as Antistripping Agents," Proceedings, Highway Research Board, Vol. 13, 1952.

5. Pauls, J. T., and Rex, H. M., "A Test for Determining the Effect of Water on Bituminous Mixtures," Public Roads, Vol. 24, No. 5, July-August-September, 1945.

6. Douglas, J. F., "Adhesion Between Binders and Aggregates," Journal of the Institution of Civil Engineers (England), No. 3, 1945-1947, January, 1947.

7. Hubbard, Prevost, "Adhesion of Asphalt to Aggregates in the Presence of Water," Proceedings, Highway Research Board, Vol. 18, Part I, 1938.

8. Endersby, V. A., Griffin, R. L., and Sommer, H. J., "Adhesion Between Asphalts and Aggregates in the Presence of Water," Proceedings, Association of Asphalt Paving Technologists, Vol. 16, February, 1947.

9. Ebberts, A. R., "The Emulsifying Effect of Asphalt Fillers," Rock Products, 33, No. 24, 1930.

10. Riedel and Weber, "On the Adhesiveness of Bituminous Binders on Aggregates," Asphalt and Teer, 677, 1933.

11. Bawa, K. S., "Sonic Studies of Bituminous Mixtures," A Thesis submitted to Purdue University for the degree of Master of Science, January, 1953.

12. Yong, Raymond, N. Y., "The Physical Significance of Sonic Tests on Bituminous Mixtures," A Thesis submitted to Purdue University for the degree of Master of Science in Civil Engineering, June, 1954.

13. Nicholson, Victor, "Adhesion Tension in Asphalt Pavements, Its Significance and Methods Applicable in its Determination," Proceedings, Association of Asphalt Paving Technologists, January, 1932.

14. Mack, Charles, "Physiochemical Aspects of Asphalt Pavements: Energy Relations at Interface Between Asphalt and Mineral Aggregate and Their Measurements," Ind. Eng. Chem. 27, 1935.

15. Holmes, A., "Evaluating the Adhesive Properties of Asphalt," Proceedings American Society for Testing Materials, Vol. 39, 1939.

16. Dow, A. W., "The Wash Test in Differentiating Between Aggregates or Colprovia Paving Mixtures," Proceedings, Association of Asphalt Paving Technologists, January, 1936.

17. Tylor, Owen R., "Adhesion of Bituminous Films to Aggregates," Purdue University Research Bulletin, No. 62, Vol. 22, September, 1938.

18. American Society for Testing Materials, "ASTM Standards on Bituminous Materials for Highway Construction, Waterproofing, and Roofing," September, 1954.

19. Pauls, J. T., and Goode, J. F., "Further Developments and Application of the Immersion Compression Test," Public Roads, Vol. 25, No. 6, December, 1948.

20. Grime, G., "Determination of Young's Modulus for Building Materials by a Vibration Method," Philosophical Magazine, Vol. 20, 1935.

21. Grime, G., and Eaton, J. E., "The Determination of Young's Modulus by Flexural Vibrations," Philosophical Magazine, Vol. 23, 1937.

22. Powers, T. C., "Measuring Young's Modulus of Elasticity by Means of Sonic Vibrations," Proceedings, American Society for Testing Materials, Vol. 38, Part 2, 1938.

23. Goodell, C. E., "Improved Sonic Apparatus for Determining the Dynamic Modulus of Concrete Specimens," Proceedings, American Concrete Institute, Vol. 47, 1950.

24. Rice, James M., "New Test Method for Direct Measurement of Maximum Density of Bituminous Mixtures," The Crushed Stone Journal, Vol. XXVIII, No. 3, September, 1953.

25. Rayleigh, "Theory of Sound," Volumes 1 and 2, Dover Publications, New York, 1945.

26. Timoschenko, S., "Vibration Problems in Engineering," D. Van Nostrand Co., Inc., New York, 1937.

27. Goens, E., "Uber die Bestimung des Elastigtatemouls von Staben mit Hilfe von Biegunagschwingunagen," Annalen der Physils, B-Folge, Bond 2, 1931.

28. Pickett, G., "Equations for Computing Elastic Constants from Flexural and Torsional Resonant Frequencies of Vibration of Prisms and Cylinders," Proceedings, American Society for Testing Materials, Vol. 45, 1945.

29. Shupe, John W., and Taylor, Daleos C., "Field and Laboratory Investigations on Hot-Mix Asphalt Concrete," Kansas State College Bulletin, No. 77, Vol. 39, July 1, 1955.

30. Southeastern Road Builders, "Preliminary Report on the Use of Radioactive Isotopes in the Laboratory Determination of Asphalt Stripping from Paving Stone," August, 1951.

APPENDIX A

DATA

Table 10

Sonic Test Specimens

Indiana AH Type B Surface Course

Lafayette Gravel

Beam Specimen #	Weight, lb (w)	Breadth, in (b)	Bulk Sp Gr	% Voids by App Sp Gr Agg	% Voids by Eff Sp Gr Agg	Days Immersion in Water at 140°F	Fundamental Frequency Vibration, cps	Sonic Modulus x 10^6 psi
1	5.35	2.05	2.42	2.3	1.0	0	1790	2.98
						1	1770	2.92
						3	1750	2.85
						5	1740	2.82
						7	1730	2.79
						9	1720	2.76
3	5.35	2.03	2.40	2.4	1.1	0	1750	2.87
						1	1710	2.74
						3	1680	2.65
						5	1680	2.65
						7	1670	2.62
						9	1660	2.59
4	5.32	2.03	2.42	2.1	0.8	0	1770	2.92
						1	1760	2.89
						3	1750	2.86
						5	1750	2.86
						7	1740	2.83
						9	1730	2.79
5	5.30	2.02	2.42	2.8	1.5	0	1800	3.03
						1	1720	2.76
						3	1710	2.73
						5	1710	2.73
						7	1700	2.70
						9	1690	2.67

Table 11

Sonic Test Specimens

Indiana AH Type B Surface Course

Greencastle Limestone

Beam Specimen #	Weight, lb (w)	Breadth, in (b)	Bulk Sp Gr	% Voids by App Sp Gr Agg	% Voids by Eff Sp Gr Agg	Days Immersion in Water at 140°F	Fundamental Frequency Vibration, cps	Sonic Modulus x 10^6 psi
7	5.33	2.02	2.42	1.0	0.1	0	1880	3.35
						1	1850	3.21
						3	1815	3.09
						5	1800	3.04
						7	1790	3.01
						9	1780	2.98
8	5.39	2.09	2.42	0.8	0.0	0	1880	3.24
						1	1820	3.04
						3	1800	2.98
						5	1790	2.94
						7	1775	2.89
						9	1760	2.84
9	5.46	2.09	2.41	1.0	0.0	0	1890	3.34
						1	1830	3.13
						3	1820	3.09
						5	1810	3.06
						7	1800	3.03
						9	1790	3.00
10	5.41	2.11	2.40	1.5	0.5	0	1880	3.22
						1	1820	3.02
						3	1800	2.96
						5	1790	2.93
						7	1780	2.89
						9	1770	2.86

Table 12

Sonic Test Specimens

Indiana AH Type B Surface Course

Massachusetts Rhyolite

Beam Specimen #	Weight, lb (w)	Breadth, in (b)	Bulk Sp Gr	% Voids by App Sp Gr Agg	% Voids by Eff Sp Gr Agg	Days Immersion in Water at 140°F	Fundamental Frequency Vibration, cps	Sonic Modulus x 10^6 psi
1	5.44	2.27	2.26	6.0	6.0	0	1570	2.10
						1	1540	2.02
						3	1520	1.97
						5	1480	1.87
						7	1380	1.62
						9	1350	1.56
3	5.47	2.28	2.26	6.1	6.1	0	1570	2.11
						1	1530	2.00
						3	1480	1.87
						5	1350	1.56
						7	1310	1.46
						9	1270	1.38
4	5.24	2.17	2.26	6.1	6.0	0	1560	2.09
						1	1530	2.01
						3	1480	1.88
						5	1340	1.54
						7	1310	1.47
						9	1280	1.41
5	5.41	2.26	2.26	6.0	6.0	0	1560	2.07
						1	1530	2.00
						3	1480	1.87
						5	1420	1.72
						7	1400	1.67
						9	1370	1.60

Table 13

Sonic Test Specimens

Corps of Engineers Surface Course

Massachusetts Rhyolite

Beam Specimen #	Weight, lb (w)	Breadth, in (b)	Bulk Sp Gr	% Voids by App Sp Gr Agg	% Voids by Eff Sp Gr Agg	Days Immersion in Water at 140°F	Fundamental Frequency Vibration cps	Sonic Modulus x 10^6 psi
6	5.46	2.20	2.32	3.5	3.5	0	1790	2.84
						1	1770	2.77
						3	1740	2.68
						5	1725	2.63
						7	1700	2.56
						9	1640	2.38
7	5.41	2.16	2.32	3.8	3.8	0	1780	2.83
						1	1770	2.79
						3	1720	2.64
						5	1700	2.58
						7	1660	2.45
						9	1540	2.12
9	5.42	2.18	2.32	3.8	3.7	0	1800	2.87
						1	1780	2.81
						3	1720	2.62
						5	1685	2.52
						7	1530	2.07
						9	1370	1.66
10	5.39	2.19	2.30	5.1	5.1	0	1740	2.65
						1	1700	2.53
						3	1420	1.77
						5	1310	1.50
						7	1275	1.42
						9	1230	1.32

Table 14

Sonic Test Specimens

Indiana AH Type B Surface Course

Massachusetts Rhyolite with Asphalt Additive

Beam Specimen #	Weight, lb (w)	Breadth, in (b)	Bulk Sp Gr	% Voids by App Sp Gr Agg	% Voids by Eff Sp Gr Agg	Days Immersion in Water at 140°F	Fundamental Frequency Vibration, cps	Sonic Modulus x 10^6 psi
14	5.33	2.28	2.21	8.1	7.8	0	1580	2.08
						1	1550	2.00
						3	1520	1.93
						5	1490	1.85
						7	1450	1.75
						9	1430	1.71
16	5.31	2.28	2.23	7.7	7.4	0	1580	2.07
						1	1550	2.00
						3	1530	1.95
						5	1500	1.87
						7	1500	1.87
						9	1500	1.87
17	5.40	2.26	2.23	7.5	7.2	0	1590	2.16
						1	1570	2.10
						3	1540	2.02
						5	1520	1.97
						7	1500	1.92
						9	1490	1.89
18	5.46	2.34	2.20	8.4	8.1	0	1590	2.10
						1	1560	2.03
						3	1530	1.95
						5	1510	1.90
						7	1500	1.87
						9	1500	1.87

Table 15

Immersion-Compression Specimens

Indiana AH Type B Surface Course

Lafayette Gravel

Spec #	Bulk Sp Gr	Av Bulk Sp Gr	Voids by App Sp Gr	Voids by Eff Sp Gr	Days Immersion at 140°F	Comp Strength, lb	Av Comp Strength, lb	% Ret Strength
2	2.40		2.7	1.4	0	2945		
6	2.39	2.39	3.0	1.7	0	2870	2958	100
1	2.39		2.8	1.5	0	3060		
5	2.39		3.0	1.6	1	2795		
4	2.37	2.39	3.5	2.2	1	2565	2688	90.3
28	2.42		1.2	0.1	1	2705		
7	2.39		3.1	1.8	3	2628		
8	2.39	2.40	2.8	1.5	3	2650	2614	88.3
29	2.41		1.8	0.4	3	2565		
10	2.39		3.1	1.6	5	2438		
32	2.41	2.40	2.0	0.7	5	2415	2468	83.5
9	2.39		2.8	1.5	5	2550		
14	2.40		2.5	1.2	7	2530		
16	2.39	2.40	2.6	1.3	7	2350	2418	81.7
17	2.41		2.2	0.9	7	2375		
13	2.39		3.3	2.0	9	2345		
15	2.38	2.39	3.4	2.1	9	2165	2277	76.9
20	2.41		2.0	0.7	9	2320		

Table 16

Immersion-Compression Specimens

Indiana AH Type B Surface Course

Greencastle Limestone

Spec #	Bulk Sp Gr	Av Bulk Sp Gr	Voids by App Sp Gr	Voids by Eff Sp Gr	Days Immersion at 140°F	Comp Strength, lb	Av Comp Strength, lb	% Ret Strength
4	2.39		2.0	1.1	0	3950		
5	2.40	2.40	1.5	0.5	0	4472	4346	100
21	2.41		1.3	0.4	0	4615		
19	2.40		1.4	0.5	1	3850		
20	2.40	2.40	1.5	0.5	1	3875	3947	90.8
22	2.41		0.9	0.0	1	4115		
17	2.41		1.2	0.2	3	3650		
18	2.41	2.41	1.4	0.5	3	3610	3654	84.0
24	2.41		0.9	0.0	3	3702		
8	2.39		1.9	1.0	5	3390		
12	2.40	2.40	1.3	0.3	5	3325	3338	76.8
14	2.40		1.4	0.4	5	3300		
9	2.40		1.6	0.7	7	3265		
10	2.39	2.40	1.9	1.0	7	3060	3122	72.0
13	2.40		1.8	0.8	7	3040		
6	2.40		1.7	0.7	9	2790		
7	2.40	2.40	1.7	0.7	9	3060	2797	64.3
11	2.39		2.1	1.1	9	2540		

Table 17

Immersion-Compression Specimens

Indiana AH Type B Surface Course

Massachusetts Rhyolite

Spec #	Bulk Sp Gr	Av Bulk Sp Gr	Voids by App Sp Gr	Voids by Eff Sp Gr	Days Immersion at 140°F	Comp Strength lb	Av Comp Strength, lb	% Ret Strength
10	2.27		5.4	5.4	0	3277		
9	2.26	2.27	6.1	6.1	0	3205	3236	100
15	2.29		4.9	4.9	0	3225		
1	2.24		6.1	6.1	1	2945		
11	2.27	2.26	5.4	5.4	1	3150	3020	93.3
12	2.27		5.9	5.9	1	2965		
2	2.27		6.0	6.0	3	2205		
20	2.29	2.28	4.8	4.8	3	2800	2615	80.8
22	2.29		5.2	5.2	3	2840		
16	2.29		5.1	5.1	5	2175		
19	2.27	2.28	5.4	5.4	5	2225	2197	67.8
14	2.27		5.6	5.6	5	2192		
4	2.27		5.9	5.9	7	2158		
21	2.29	2.28	4.8	4.8	7	1615	1928	59.6
17	2.27		5.7	5.7	7	2010		
7	2.26		5.6	5.6	9	825		
8	2.26	2.27	6.1	6.1	9	962	922	28.5
13	2.27		5.1	5.1	9	978		

APPENDIX B

THEORY FOR SONIC TEST

THEORY FOR SONIC TEST

The natural frequency of vibration of a bar is a measurable quantity which may be used to determine the modulus of elasticity. In this study, only the transverse vibrational movements are used. The theory for transverse vibrations is taken from Yong's (2) study on "The Physical Significance of Sonic Tests on Bituminous Mixtures."

Transverse Vibrations

"Transverse vibrations occur in a manner much the same as . . . bending. Consequently, when considering the effects due solely to transverse vibrations, the bar may be analyzed on the basis of . . . bending. Consider a bar whose cross-sectional dimensions are small in comparison with its length. The differential equation for the deflection curve is given by the equation.

$$\frac{M}{EI} = -\frac{\partial^2 y}{\partial x^2}$$

where M = bending moment at any cross section.

E = Young's modulus of elasticity.

I = moment of inertia of the section.

EI = flexural rigidity.

$$\frac{\partial^2}{\partial x^2}\left[EI\frac{\partial^2 y}{\partial x^2}\right] = -\frac{\partial^2 M}{\partial x^2} = \omega$$

where ω is the continuous load intensity of the bar.

Referring to d'Alembert's principle,

$$\omega = -A\rho\frac{\partial^2 y}{\partial t^2}$$

where A is the cross-sectional area and ρ the density of the bar.

therefore,
$$\frac{\partial^2}{\partial x^2}\left[EI\frac{\partial^2 y}{\partial x^2}\right] = -A\rho\frac{\partial^2 y}{\partial t^2}$$

$$EI\frac{\partial^4 y}{\partial x^4} = -A\rho\frac{\partial^2 y}{\partial t^2}$$

and,
$$\frac{\partial^2 y}{\partial t^2} + a^2\frac{\partial^4 y}{\partial x^4} = 0 \quad \text{.....................6}$$

where,
$$a^2 = \frac{EI}{A\rho}$$

"The [end] conditions for a free-free bar vibration [sic] transversely are that $\frac{\partial^2 y}{\partial x^2} = 0$ and $\frac{\partial^3 y}{\partial x^3} = 0$. Assuming that the solution takes the form of a harmonic motion (25), let a new function then be defined such that,

$$y = \mu \cos\frac{am^2 t}{\ell^2} \quad \text{..............................7}$$

where ℓ is the length of the bar, and m is an unknown quantity. Substituting equation 7 into equation 6 yields the following relationship.

$$\frac{\partial^4 u}{\partial x^4} = \frac{m^4 u}{\ell^4} \quad \text{..............................8}$$

For μ to be a solution

$$\mu = e^{\frac{\rho m x}{\ell}}$$

[ρ is one of the fourth roots of unity, viz., +1, −1, +i, −i]

Hence,

$$\mu = A\cos m\frac{x}{\ell} + B\sin m\frac{x}{\ell} + Ce^{\frac{mx}{\ell}} + De^{-\frac{mx}{\ell}} \quad \text{........9}$$

where A, B, C, and D are arbitrary constants. For pure periodicity of motion, C and D are zero. Consequently,

$$\frac{2\pi}{J} = a\,\frac{m^2}{l^2}$$

where J = period of vibration.

Therefore, $aJ = \frac{2\pi l^2}{m^2} = \frac{a}{n}$

and $n^2 = \frac{a^2 m^4}{4\pi^2 l^4}$

but $a^2 = \frac{EI}{A\rho}$

Hence, $n^2 = \frac{m^4}{4 l^4} \frac{EI}{\pi^2 A\rho}$

Therefore, $E = \frac{n^2\, 4\pi^2 l^4\, A\rho}{m^4\, I}$ 10

but, $l A \gamma = W$ = weight

Hence, $E = \frac{4\pi^2 l^3}{m^4 I g}\, W n^2$

Therefore, $E = CW\, n^2$ 11

where, $C = \frac{4\pi^2 l^3}{m^4\, I\, g}$

g = attraction due to gravity, and

γ = weight of material per unit volume.

"If the effects of rotatory inertia and the shearing force be taken into consideration, equation 6 is transformed into the following form (26).

$$EI\,\frac{\partial^4 y}{\partial x^4} + \frac{\gamma A}{g}\frac{\partial^2 y}{\partial t^2} - \left[\frac{\gamma I}{g} + \frac{EI}{GK'}\,\frac{\gamma}{g}\right]\frac{\partial^4 y}{\partial x^2 \partial t}$$

$$+ \frac{\gamma^2 I}{g^2 K' G}\,\frac{\partial^4 y}{\partial t^4} = 0 \qquad \text{..................12}$$

where k' is a factor dependent upon the cross sectional shape.

"In general, however, the solution given by equation 11 is quite effective, considering the size of the laboratory specimens, and is the one equation most commonly used in sonic vibrational studies.

"Goens' (27) solution of equation 6 involves the differentiation between odd and even numbered modes of vibration.

$$\frac{M}{\tanh \frac{\alpha}{2}} + \frac{N}{\tan \frac{\beta}{2}} = 0 \quad \ldots\ldots\ldots\ldots\ldots 6a$$

$$\frac{M}{\coth \frac{\alpha}{2}} - \frac{N}{\cot \frac{\beta}{2}} = 0 \quad \ldots\ldots\ldots\ldots\ldots 6b$$

"Equation 6a is the solution for the odd numbered modes of vibration and equation 6b applies to the even numbered. α and β satisfy the requirements in equation 12 and depend primarily on r, the ratio of the depth of vibration to ℓ, the length of the specimen. M and N have to satisfy the requirements for the free-free condition. If the depth of vibration is small compared to the length of the specimen, k/ℓ becomes small, where k is the radius of gyration and k/ℓ is the inverse of the slenderness ratio. As k/ℓ approaches zero, according to Goens, $\alpha = \beta = m$, the value of m being found from equation 10.

$$E = \frac{n^2 \; 4\pi^2 \ell^4 \rho}{m^4} \; \frac{A}{I} \quad \ldots\ldots\ldots\ldots\ldots\ldots 10$$

However, $\quad \frac{A}{I} = \frac{1}{r^2}$

and hence $\quad E = \frac{n^2 \; 4\pi^2 \ell^4 \rho}{m^4 \quad r^2}$

Therefore, $$m = \left[\frac{4\pi^2 n^2 \ell^4 \rho}{r^2 E} \right]^{1/4} \qquad \ldots\ldots\ldots 10a$$

"If s is the limiting value of m, then equations 6a and 6b would be resolved into,

$$\tan s/2 + \tanh s/2 = 0 \qquad \ldots\ldots\ldots 6a_1$$

$$\cot s/2 - \coth s/2 = 0 \qquad \ldots\ldots\ldots 6b_1$$

As has been defined in the derivation of equation 11,

$$C = \frac{4\pi^2 \ell^3}{m^4 g}$$

"In this limiting case whereby k/ℓ approaches zero, it will be necessary to define a new value for c which will be designated c'.

$$c' = \frac{4\pi^2 \ell^3}{g \; I \; s^4}$$

"Solution of the limiting case for k/ℓ approaching zero, i.e., solving equations $6a_1$ and $6b_1$ would yield values of s pertinent to the various modes of vibration. Equation 11a can now be solved for any given specimen since the physical dimensions will be known. To relate c to c', Goens introduced a correction factor T, for c varies proportionately with c'. Defining T as being $\frac{s^4}{m^4}$, he stated that: $c = c' \, T$

"The general Taylor series expansion given by Goens for the solution of T for $k' = 5/6$ when $\mu = 0$ is:

$$T = 1 + 79.02 \, (k/\ell)^2 - \frac{1201 \, (k/\ell)^4}{1 + 76.06 \, (k/\ell)^2}$$

where k' has been defined for the relationship in equation 12. For $k' = 8/9$ when $\mu = 1/6$

$$T = 1 + 81.79 \, (k/\ell)^2 - \frac{1314 \, (k/\ell)^4}{1 + 81.09 \, (k/\ell)^2}$$

"For values of $k/\ell \leq$ 0.[illegible] the solution for T is quite valid. However, for values of $k/\ell >$ 0.[illegible] values for T tend to be too large. Pickett (28) ascribes this to the fact that the boundary conditions imposed for the solution of the differential equation were not too rigid. However, he claims that this failure to satisfy the end conditions does not affect the computed frequency appreciably. A table giving values for T for different values of μ and k/ℓ is presented by him. In order to relate T to values other than those given by Pickett (28), it would be possible to use Goens' series solution. In terms of a definite value of μ, but with the introduction of a correction factor, the following equation for T' may be used (11) where T' represents the corrected value for T.

$$T' = T \left[\frac{1 + (0.26\mu + 3.22\mu^2)\ k/\ell}{1 + 0.1328\ k/\ell} \right]$$

"The equation for T' was derived by a proportionality factor based upon the value of T for $\mu = 1/6$ as given by Pickett.

k/ℓ	T	k/ℓ	T
0	1.0000	0.12	2.0262
0.01	1.0082	0.14	2.3601
0.02	1.0325	0.16	2.7319
0.03	1.0725	0.18	3.1385
0.04	1.1276	0.20	3.5763
0.05	1.1969	0.25	4.7777
0.06	1.2796	0.30	6.0660
0.07	1.3752		
0.08	1.4829		
0.09	1.6023		
0.10	1.7328		

"The above values of T versus k/ℓ are based on the assumption that $\mu = 1/6$."

In this investigation, Young's modulus of elasticity for the beam specimens is computed by equation 11.

$$W = Cn^2$$

with $C = 0.00245\, \ell^3 \dfrac{T'}{bt^3}$

where W = weight of beam,

n = resonant frequency,

ℓ = length of beam,

b = breadth of beam,

t = thickness of beam,

T' = corrected value of T.

APPENDIX C

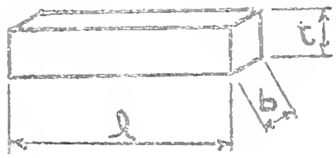
SAMPLE COMPUTATIONS

SAMPLE COMPUTATIONS

Sonic Test

Sample calculation uses data from Table 12, beam specimen #3.

Length (ℓ)	= 12.0 in
Thickness (t)	= 2.5 in
Poisson's ratio (μ)	= 0.40
Breadth (b)	= 2.28 in
Weight (w)	= 5.47 lb
Resonant frequency (n)	= 1570 cps



E – Young's modulus of elasticity

f – Transverse frequency of vibration

T – Correction factor based on μ, k, and ℓ

k – Radius of gyration of beam specimen

Calculation of E from transverse frequency of beam specimen #3.

$$E = 0.00245\, \ell^3 \frac{T'}{bt^3} Wn^2$$

$$= 0.00245\, (12)^3 \frac{1.317}{2.28\ (2.50)^3}\ 5.47\ (1570)^2$$

$$= 2.11 \times 10^6 \text{ psi}$$

The value of the correction factor $T' = 1.317$ used above is calculated with the following equation:

$$T' = T\left[\frac{1 + (0.26\,\mu + 3.22\,\mu^2)\, k/\ell}{1 + 0.1328\ k/\ell}\right]$$

where T is taken from Appendix B, page 87 and $k/\ell = \dfrac{t}{\sqrt{12/1}}$

In this case $k/\ell = \dfrac{2.5}{\sqrt{12/12}} = 0.060$ and corresponding to

$T = 1.2796$ from Appendix B, page 87.

$$T' = 1.2796 \; \frac{1 + (0.26 \times 0.4 + 3.22 \times \overline{0.4}^2)\; 0.060}{1 + 0.1326 \quad (0.060)}$$

$$= 1.317$$

APPENDIX D

DETAILED PROCEDURES

DETAILED PROCEDURES

The detailed procedures which follow are intended to be supplemental to the general procedures which have been given. They are intended specifically for the experimenter who may wish to duplicate or continue this work and are subdivided as follows: (a) Preparation of bituminous mixtures, (b) Forming and testing the beam specimens, and (c) Forming and testing the Immersion-Compression specimens.

Preparation of Bituminous Mixtures

1. The amount of aggregate required to make one beam specimen, computed on the basis of volume and specific gravities of both aggregates and asphalt, was found to be approximately 2500 grams. The batch of aggregate for each beam specimen was made up by weighing out the required amount of each of the individual component sizes of the aggregate using a torsion balance. About 5000 grams was used for the 10-inch cylinders from which the 4-inch Immersion-Compression specimens were sawed. Mixing was accomplished in two batches for the 10-inch cylinders. About 2000 grams aggregate was required for specimens used in the A.S.T.M. Test D 1075-54.

2. The amount of asphalt required for the various specimens was determined on the basis of 6 1/2 per cent of the total weight of aggregate plus asphalt. Asphalt required for one specimen was weighed into an asphalt dispensing pan, the most convenient size being a one quart aluminum kitchen saucepan having an inside diameter of about five and one-half inches. The bulk asphalt contained in five gallon cans was removed by cutting small portions out using a heated, bent-blade spatula.

3. The aggregate for one specimen contained in a one gallon can and the asphalt contained in its dispensing pan were heated to 290 ± 20^{0}F in a

gas oven. Mixing bowl, mixing paddle, and a large metal spoon were heated to the same temperature.

4. The heated mixing bowl was removed from the oven, placed on a beam balance with the bowl's tare weight set on the balance. Next, the contents of one can of aggregate was placed in the mixing bowl to the nearest gram. Then hot asphalt was poured into the bowl in the amount determined, based on the amount aggregate used, using the beam balance.

5. The mixing paddle was then affixed to the mixer and the hot mixing bowl with its contents placed in the mixer. The mixer was then started and allowed to run for two minutes. Figure 23 shows the equipment used to mix the asphalt and aggregate. On completion of the mixing time, the mixture is ready for forming into specimens.

Forming and Testing the Beam Specimens

1. The beam specimen mold (Fig. 2) and large spoon were removed from the oven. The sides of the mold were then coated with a thin layer of SAE 20 crankcase oil and 2 1/2-inch by 12-inch piece of wrapping paper was placed in the bottom of the mold. The contents of the mixing bowl were spooned into the beam mold and proportioned evenly throughout the length of the mold. Another piece of wrapping paper was set on top of the mixture after which the I-beam was snugly fitted on the mixture in the mold.

2. The beam specimen mold was placed in the hydraulic ram (Fig. 3), centered, and a static load of 600 psi was applied to one side of the specimen for one minute. On removal of the mold assembly from the hydraulic ram and using the detachable part of the mold, the specimen was turned over and a static load of 600 psi was applied to this side of the

Fig. 23 - Equipment Used To Mix Asphalt and Aggregate

specimen for one minute. The beam mold was then removed from the hydraulic ram.

3. Next, the mold collar and I-beam were detached and the carriage, rocker guide, and rocker arm were attached as shown in Figure 24. More details on the roller compactor attachment are shown in Figure 25 and Figure 26. After placement of the beam mold and attachments in the Riehle Testing Machine (Fig. [illegible]), a load equivalent to 300 pounds per lineal inch across the specimen was applied and the beam mold and specimen was moved ten times under the load applied through the rocker arm.

4. After removal from the Riehle testing machine, the carriage, rocker guide, and rocker arm were detached and replaced with the mold collar and I-beam. On placement in the hydraulic ram (Fig. [illegible]), a static loading of [illegible] psi was applied in the same face as the rolling action for a period of two minutes. The beam mold was then removed from the hydraulic ram, the I-beam, mold collar, and bottom portion of mold detached. The remainder of the mold and specimen was immersed in a cold water bath and allowed to cool for about five minutes.

5. The specimen was then removed by placing the I-beam on the ram with the mold resting on the I-beam, affixing the mold collar to the mold proper, and extruding the specimen into the mold collar. The valve was released and the specimen taken out of the mold collar, marked for identification, and allowed to cool to room temperature.

6. The beam specimens were then placed on glass plates, placed in a constant temperature oven at 140°F and allowed to cure for a period of 24 hours. After removing from the oven and cooling to room temperature, the bulk specific gravity was determined for each specimen following the procedure described in A.S.T.M. Test D 1075-54. The thickness of each beam was recorded.

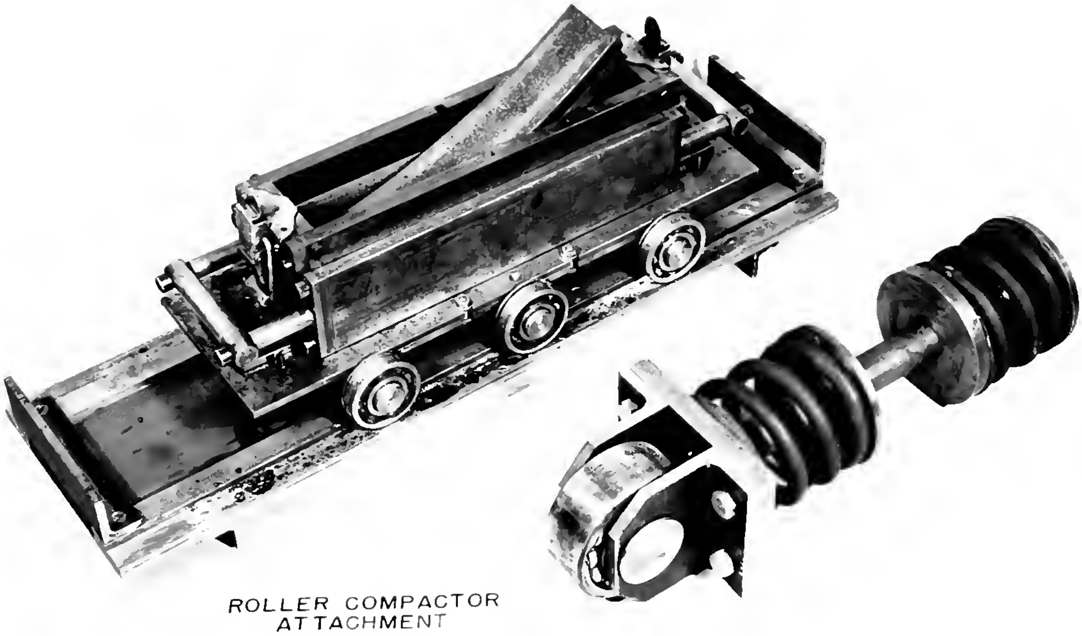


Fig. 24 - Beam Specimen Mold, Carriage, Carriage Guide, Rocker Guide, Rocker Arm, and Loading Attachment.

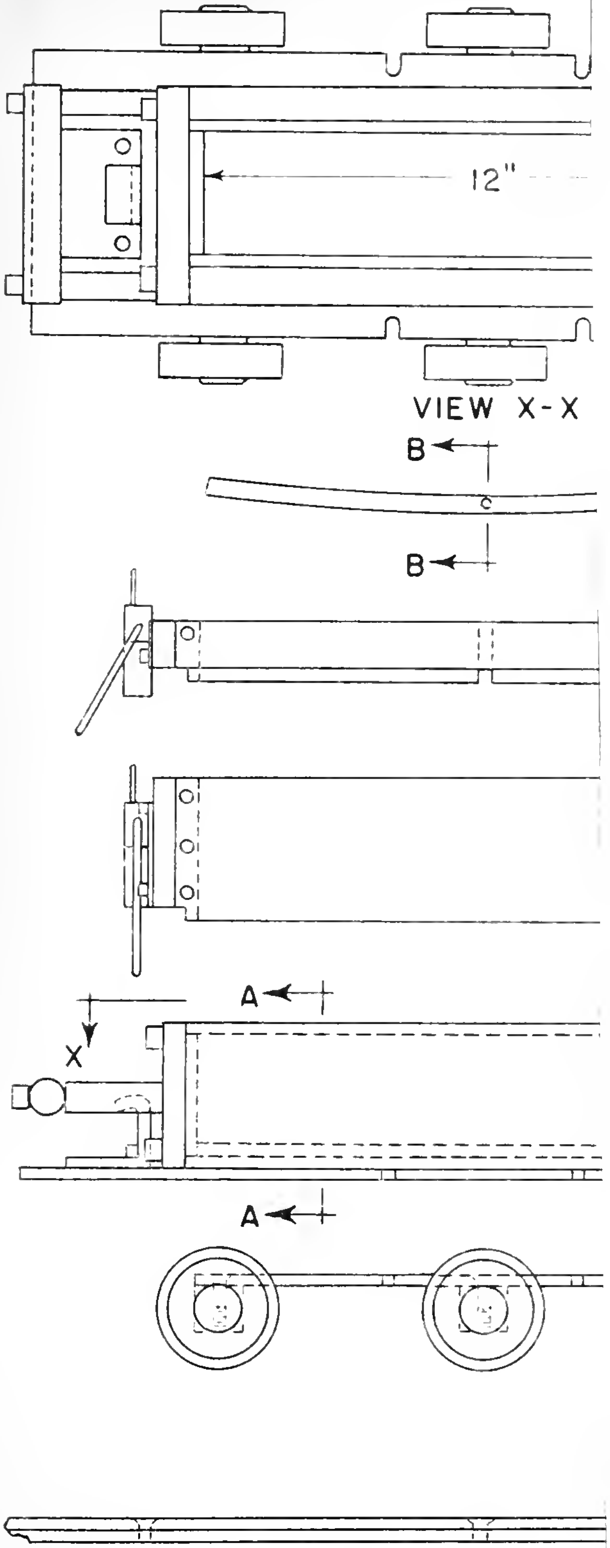


FIG. 25 BEA

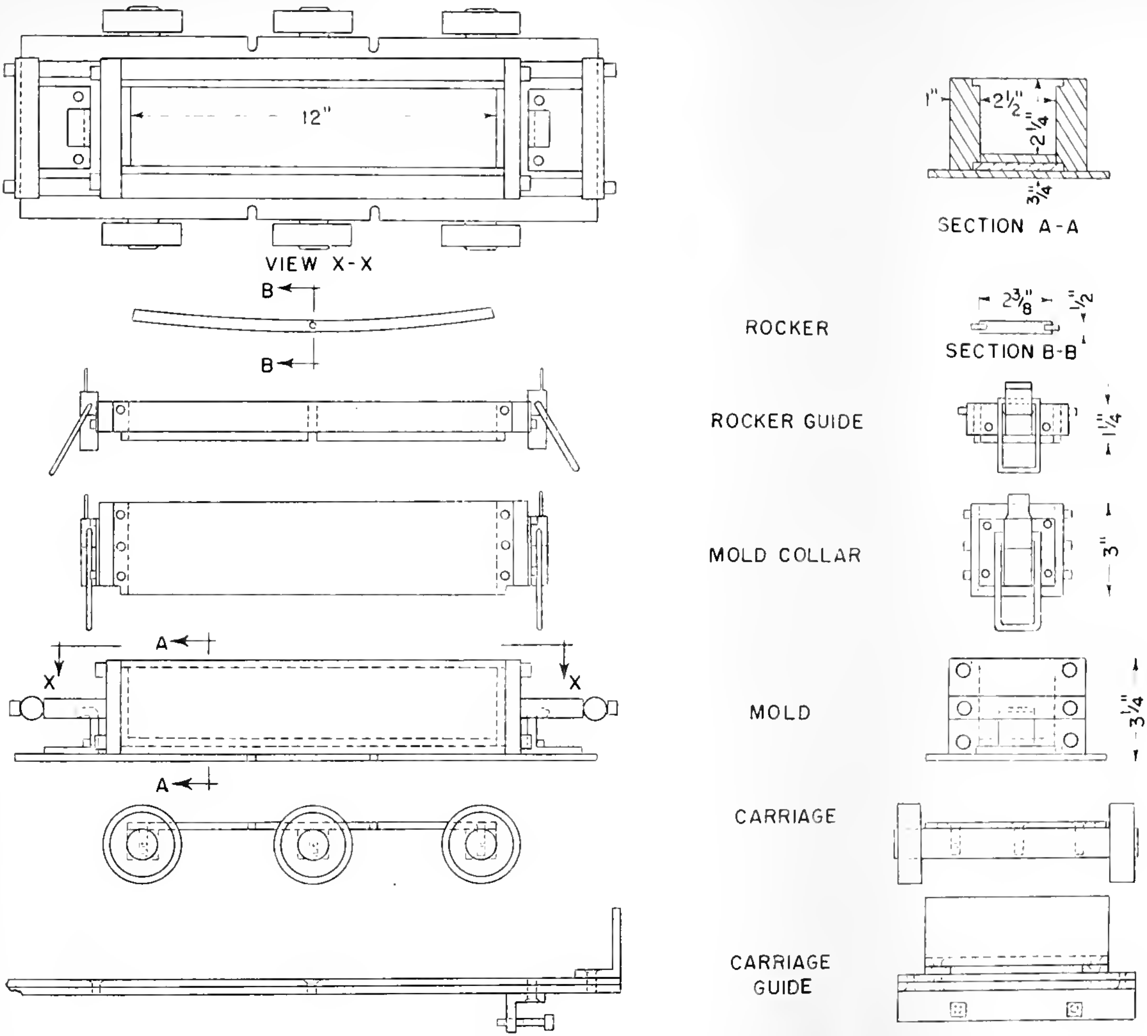


FIG. 25 BEAM MOLD AND ATTACHMENTS

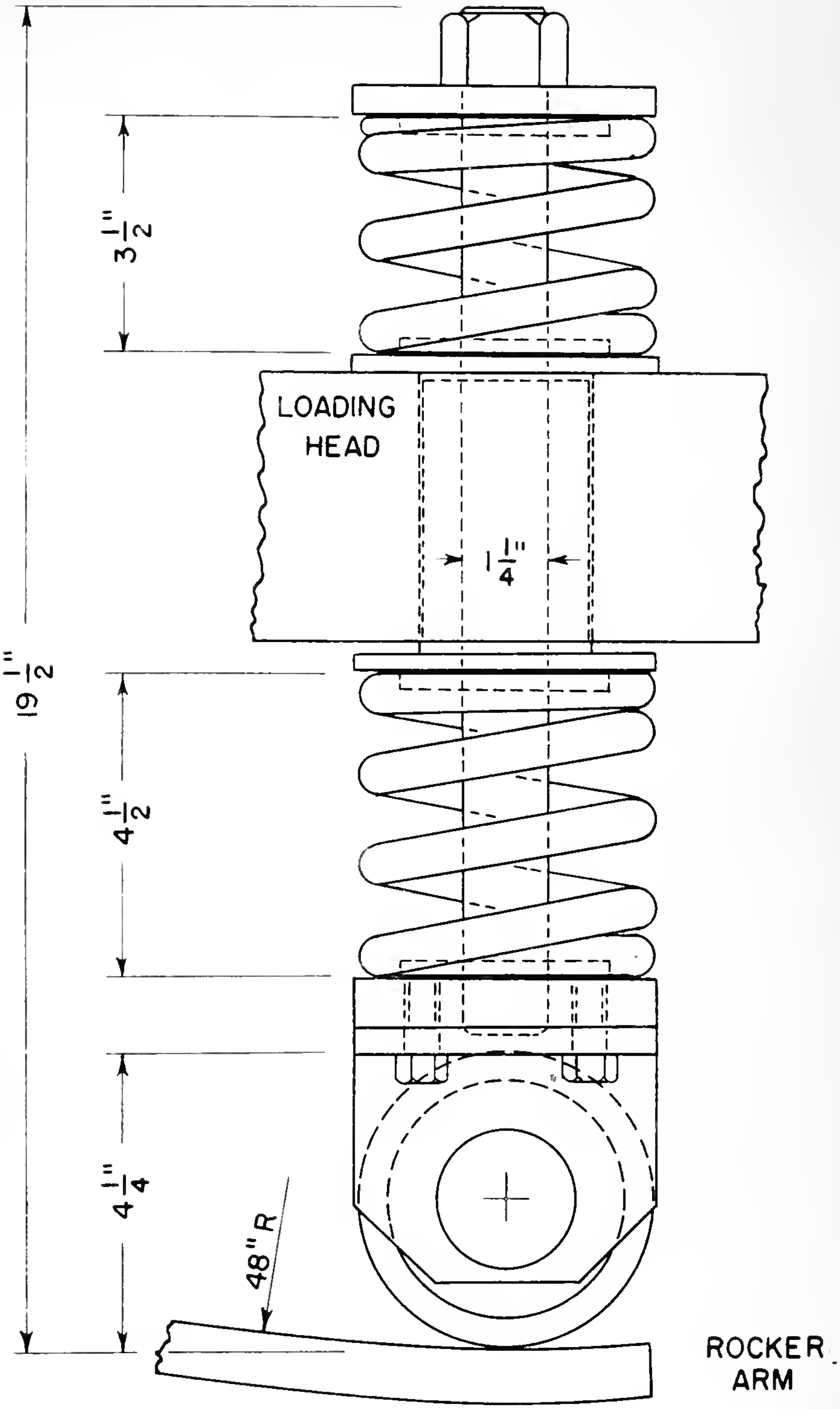


FIG. 26 ATTACHMENT FOR APPLYING ROLLING ACTION TO ROCKER ARM

7. Prior to making the initial Sonic Test on each specimen, they were cooled to $40 \pm 1°F$ for a period of 2 hours in an ice bath. Each specimen was removed from the bath, wiped dry and placed on the driver (See Figure 5 and 6) for determination of its fundamental frequency of vibration.

8. Each beam was actuated using the Jackson audio oscillator having a frequency range of from 20 to 20,000 cycles per second with a maximum power output of 500 milliwatts. Actual contact with the beam specimen was made using a modified ST-104 Jensen speaker connected to the output of the audio oscillator.

9. Detection of the beams frequency of vibration was accomplished using a VM-1 brush vibromike transmitting the frequency to the cathode-ray oscillograph. As the mechanical input to the beam was varied, the electrical output of the pick-up would vary, being a maximum when the specimen was vibrating at its fundamental frequency. The cathode-ray oscillograph would register maximum amlitude when the specimen was vibrating at this fundamental frequency. This frequency of vibration would be read from the oscillator dial and recorded. When the oscillator signal was fed to one set of plates on the cathode-ray tube and the pick-up signal to the other set of plates, a Lissajous circle was seen on the tube screen when the signals were of the same frequency and in phase (Fig. 5).

10. On completion of each period of immersion, the beam specimens were cooled down to a temperature of $40 \pm 1°F$ for a period of two hours in an ice bath prior to testing sonically.

Forming and Testing the Immersion Compression Specimens

1. Following completion of mixing for the first one-half batch

of 2500 grams for the 5000 gram 10-inch cylinders, the contents of the mixing bowl were transferred to the large heated mixing pan and replaced in the oven. The bowl was then replaced on the beam balance in preparation for mixing the second batch.

2. While the mixing process was in progress for the second batch, the cylindrical mold (Fig. 7) was removed from the oven and placed on the work table. Previous to placing the mold in the oven, the inside surface had been oiled with a coat of SAE 20 crankcase oil. To prevent adherence of the asphalt mixture to the bottom of the mold, a four inch diameter disk of wrapping paper was placed on the bottom of the mold.

3. The second mixing period being over, the large mixing pan was removed from the oven and the second batch of mixture from the bowl transferred therein. The two batches were then mixed by hand following which they were placed in the mold in four equal layers, each layer being rodded 25 times.

4. A four inch diameter wrapping paper disc was placed on top of the rodded mixture after which the piston plunger was put in place. The entire mold was then lifted and placed on a hydraulic ram (Fig. 27) which provided the force for compaction.

5. The pin securing the bottom plunger was removed, permitting double plunger action as a load of 3000 psi was applied and maintained for 2 minutes. The assembly was then removed from the hydraulic ram and placed in a cold water bath for a period of eight minutes to cool the specimen.

6. After cooling, the assembly was replaced in the hydraulic ram and a load applied to one plunger sufficient to break the specimen

loose inside the mold. The specimen was then removed by disassembling the mold as shown in Figure 7.

7. The specimens were then allowed to cool to room temperature before placement in a freezer at -20°F. After a period sufficient for complete freezing, the specimens were removed from the freezer and a 4-inch high specimen was cut from each end of the 10-inch cylinders using a masonry saw equipped with a blade for cutting asphaltic concrete materials.

8. After the above 4-inch high specimens thawed out to room temperature, they were placed on glass plates, placed in a constant temperature oven at 140°F and allowed to cure for a period of 24 hours. After removing from the oven and cooling to room temperature, the bulk specific gravity was determined for each specimen following the procedure described in A.S.T.M. Test D 1075-54.

9. Specimens selected for no immersion and following completion of the selected immersion period were tested according to the procedure described in the standard A.S.T.M. Test D 1075-54.

The above procedure was modified in the molding of 4-inch high specimens without sawing by placing in the mold prior to compaction only enough material to produce a 4-inch high specimen. The steps on removal of the specimen from the mold, curing, and testing followed the procedure described in the standard A.S.T.M. Test D 1075-54.

Fig. 27 - Hydraulic Ram With Cylindrical Mold
In Place For Compaction